# Measurement of Neutrino-Hydrogen Interactions in a Straw Tube Tracker for the DUNE ND

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PONDD, Fermilab Dec 03 2018

# Why Hydrogen?

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{osc}(E_\nu) \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

**Number of events observed in the detector**

**Neutrino flux**

**Oscillation probability**

**Cross section**

**Detector response**

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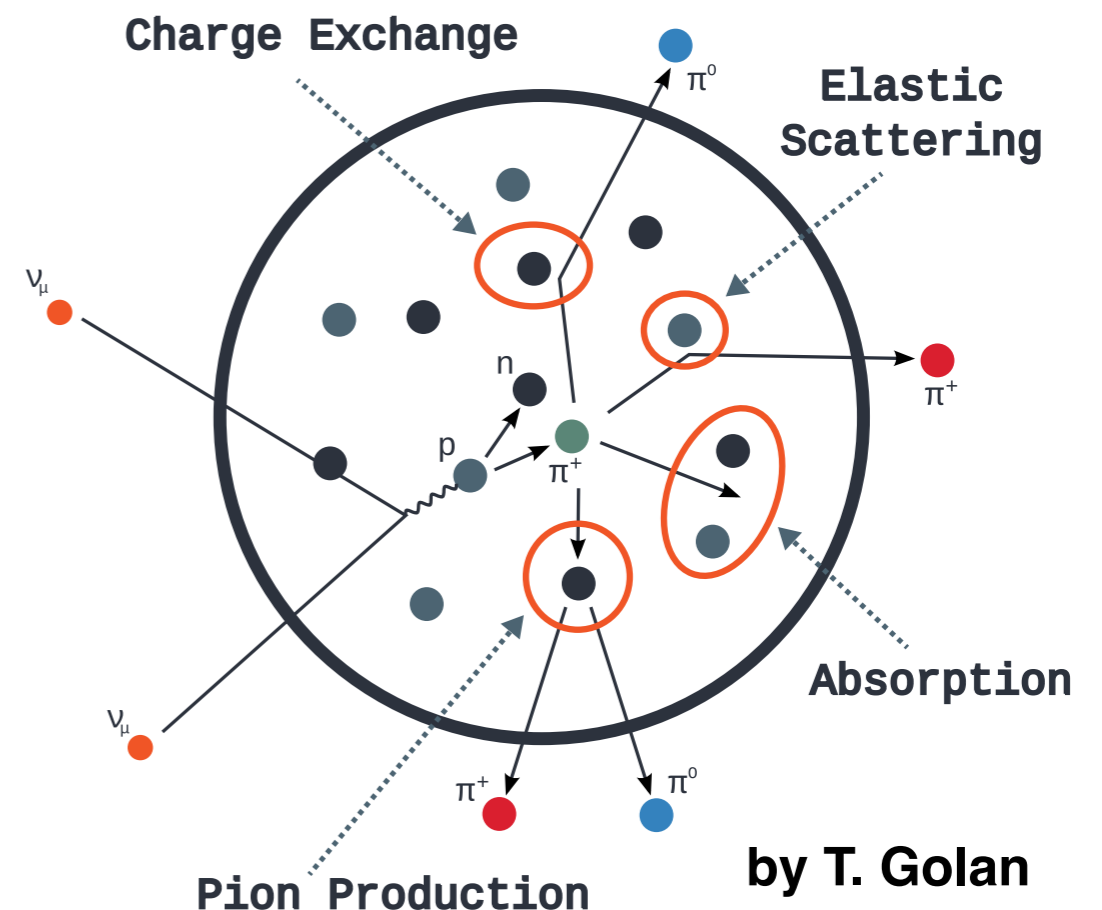**Number of events observed in the detector**

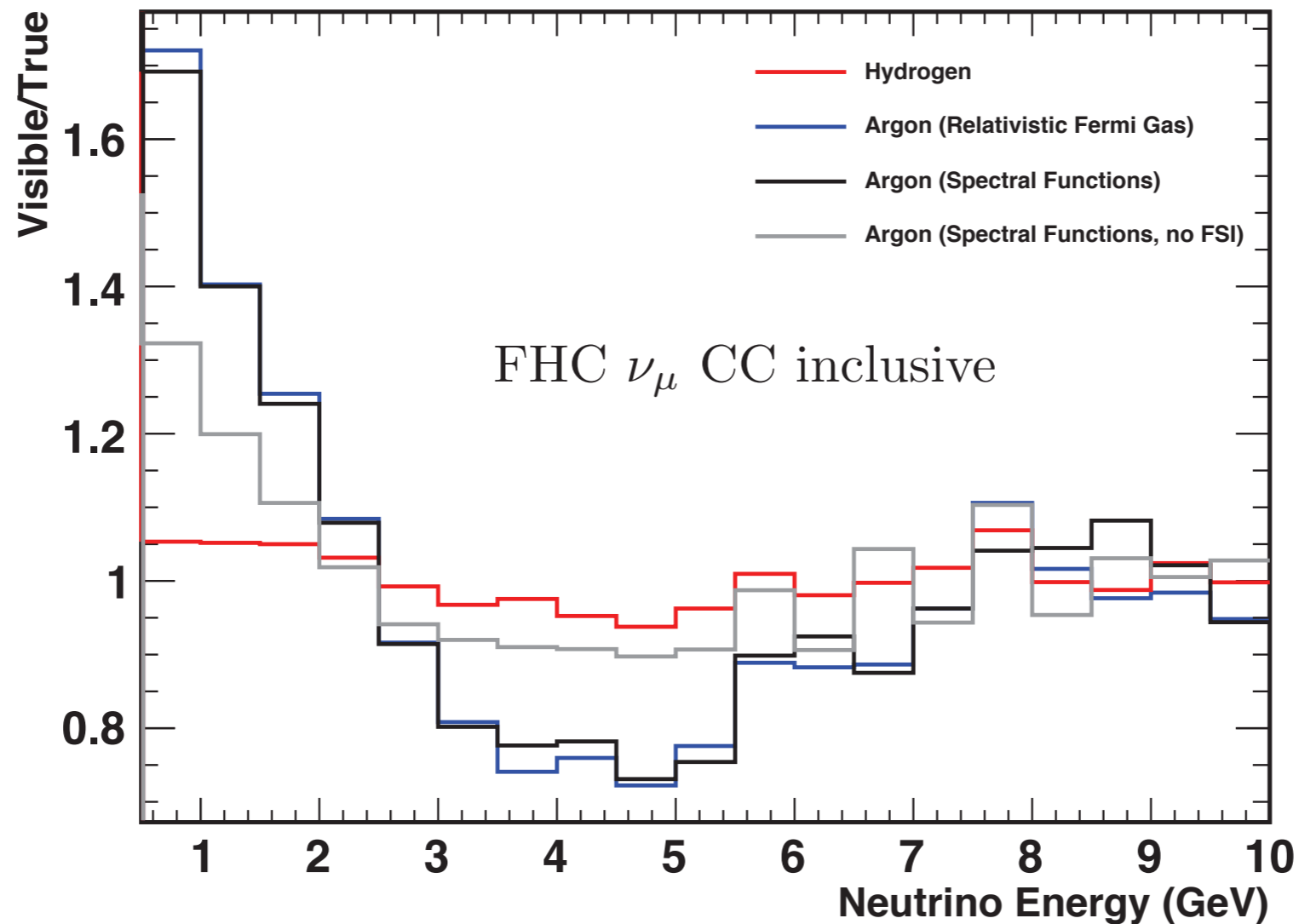**Neutrino flux**

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- Modern neutrino experiments use heavy nuclear targets for statistics. For example, Ar in DUNE.

- Nuclear effects (Fermi motion, nucleon-nucleon correlations, final state interactions etc.) are important:

  - Energy reconstruction
  - Flux and other measurements

Charge Exchange

Elastic Scattering

$\pi^0$

$\nu_\mu$

n

p

$\pi^+$

$\pi^+$

Absorption

$\nu_\mu$

$\pi^+$   $\pi^0$

Pion Production

**by T. Golan**

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# Neutrino Energy Reconstruction



FHC $\nu_\mu$ CC inclusive

Legend:
- Hydrogen
- Argon (Relativistic Fermi Gas)
- Argon (Spectral Functions)
- Argon (Spectral Functions, no FSI)

Y-axis: Visible/True
X-axis: Neutrino Energy (GeV)

- Nuclear smearing of neutrino energy in Ar is large.
- Rely upon MC to do the correction is model-dependent.

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**Number of events observed in the detector**

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**Detector response**

$$\sigma_{\nu-N} \times R_{NuclearEffects}(E_\nu, E_{rec})$$

- Neutrino-Hydrogen measurements will provide:

  - Measurements free from nuclear effects:

    - Neutrino energy scale.

    - Neutrino flux.

  - Disentangle nuclear effects from others.

- Measurement of neutrino-hydrogen interactions is also important to cross-section physics.
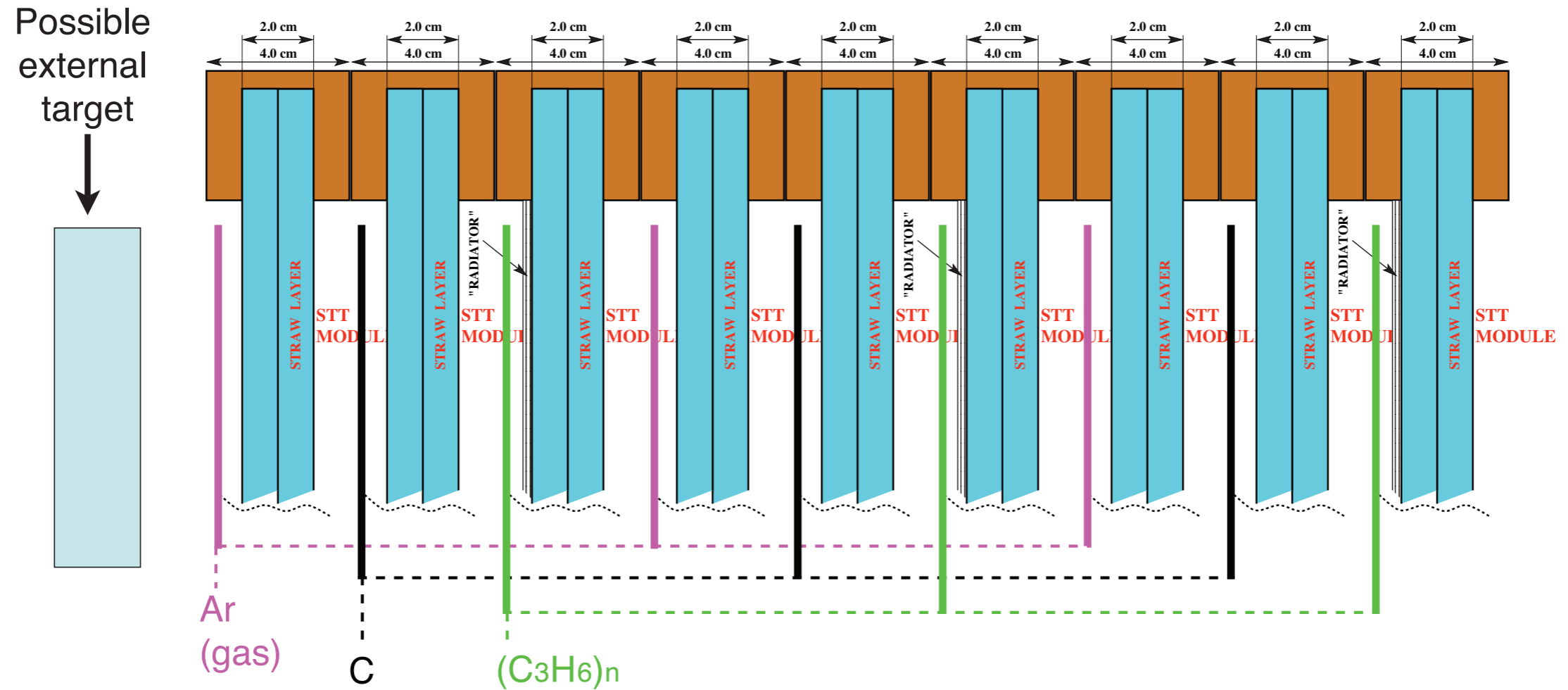
# A "Hydrogen Detector" at DUNE ND?

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) P_{osc}(E_\nu) \sigma(E_\nu) R_{det}(E_{rec}, E_\nu)$$

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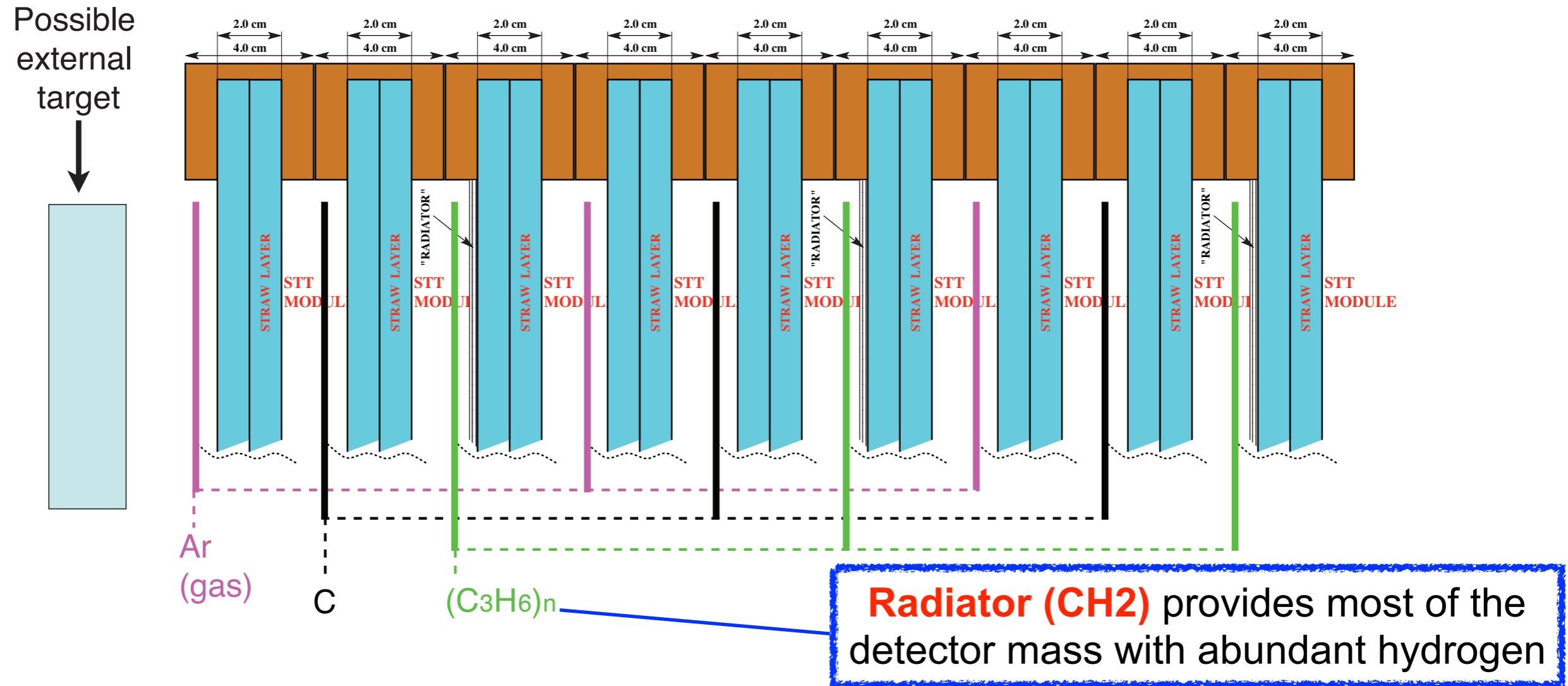**Oscillation probability**

**Detector response**

$$\sigma_{\nu-N} \times R_{NuclearEffects}(E_\nu, E_{rec})$$

- We don't have many neutrino-hydrogen datas:

  - Early bubble chamber datas suffer from low-statistics.

  - No such experiments for ~30 years.

- Neutrino-hydrogen measurements for DUNE should:

  - Be exposed to same flux

  - Have as similar as possible detector response with nuclear targets (Ar).

- A pure hydrogen detector (liquid or gas) with large mass causes safety concerns.
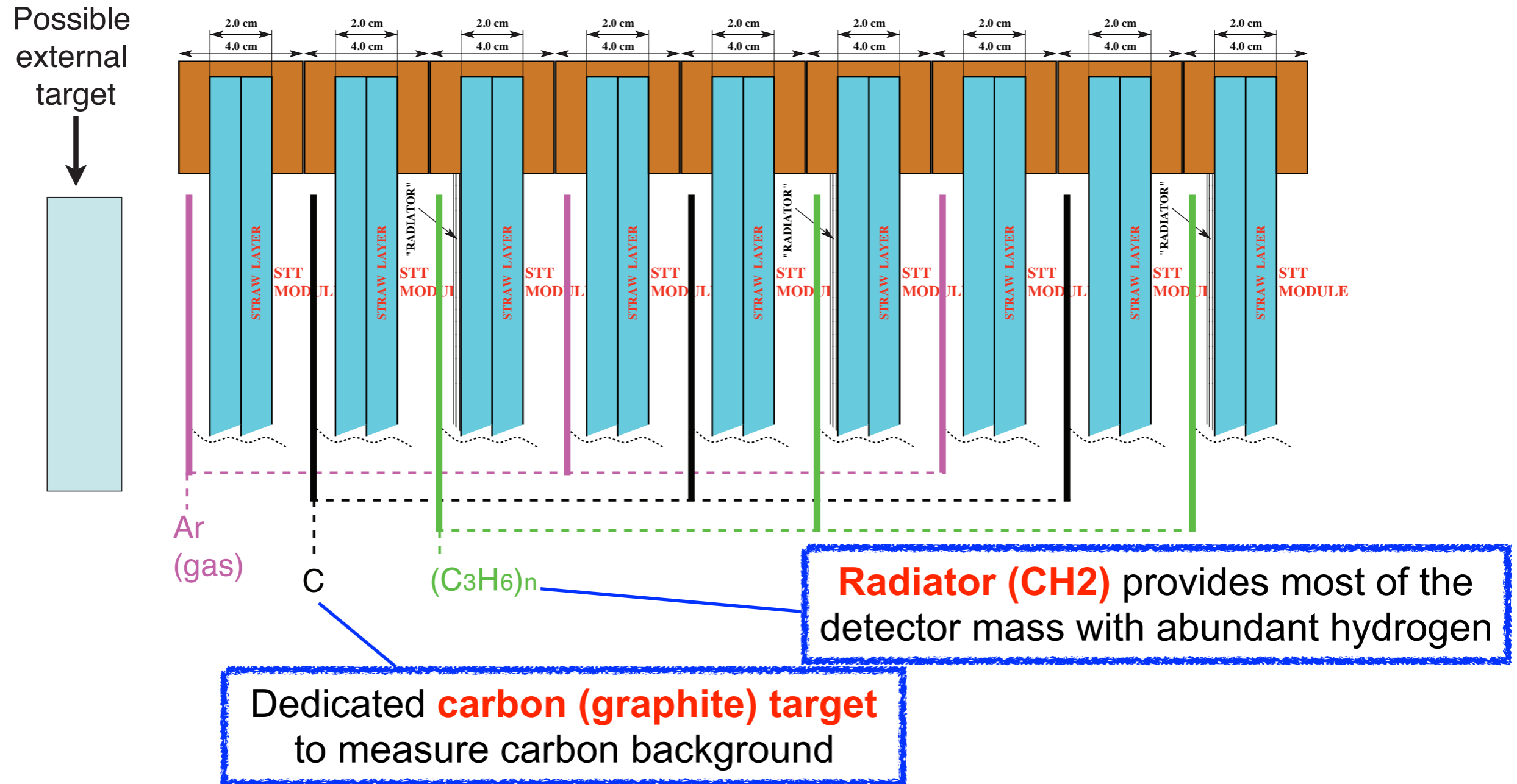
  - Can also be expensive.
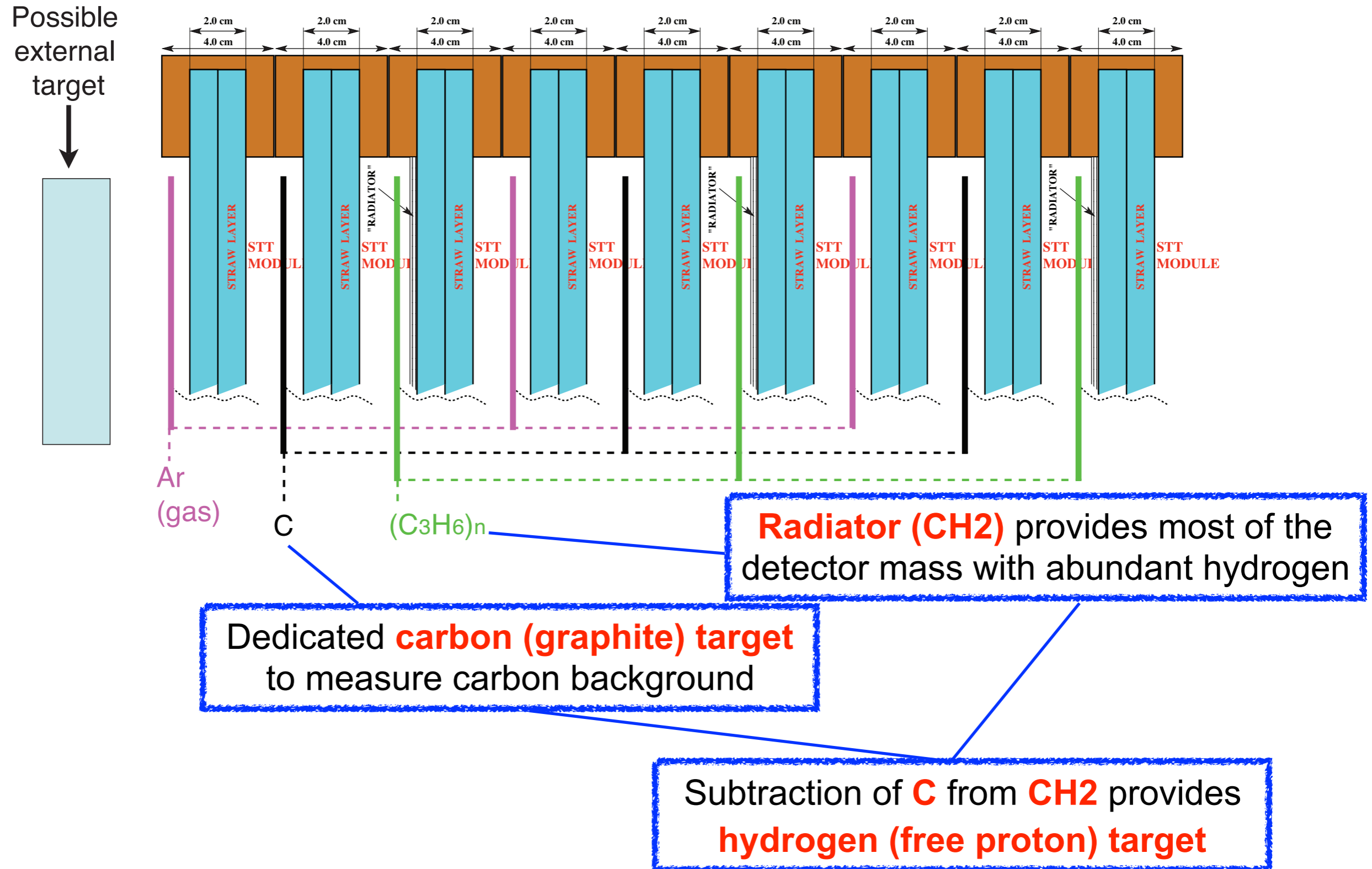
# Measurement of Neutrino-Hydrogen in STT

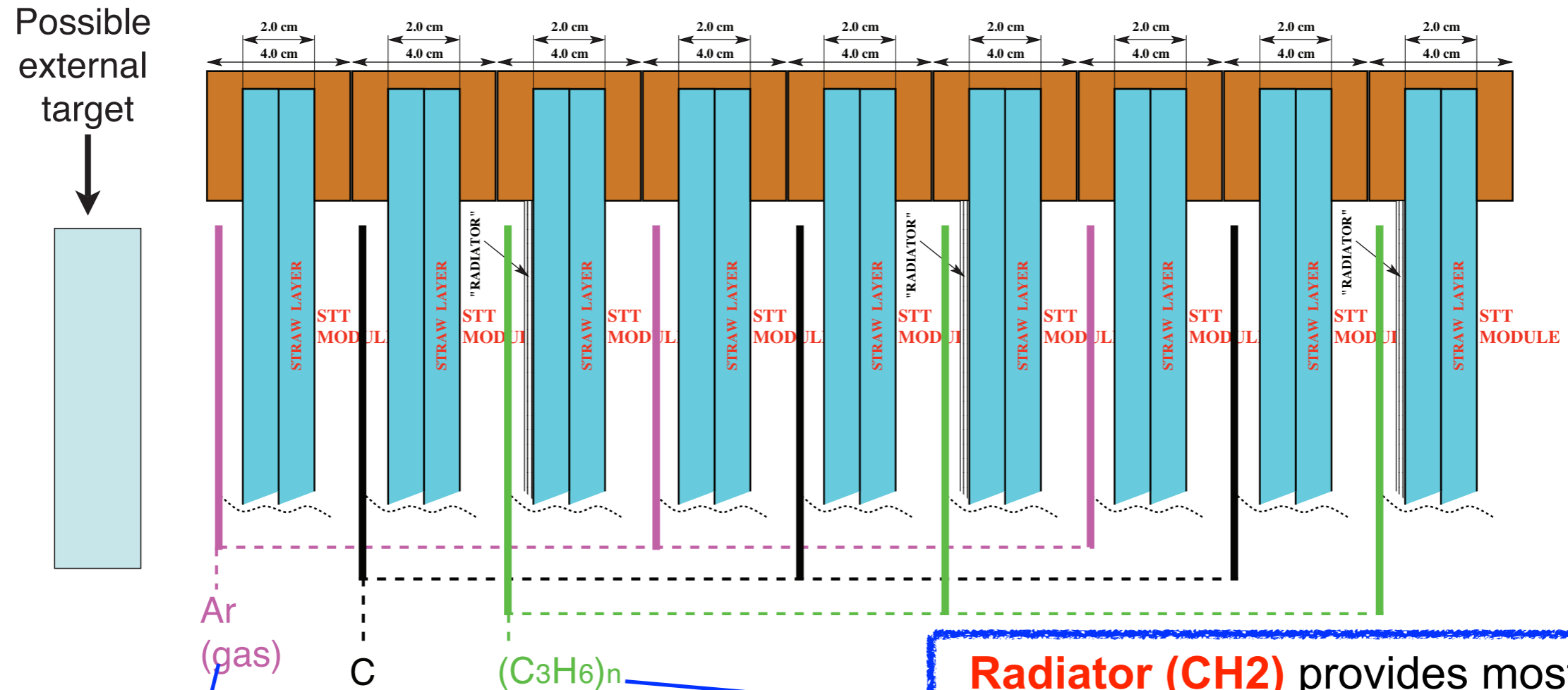# Measurement of Neutrino-Hydrogen in STT

# Measurement of Neutrino-Hydrogen in STT



Possible external target

2.0 cm   4.0 cm   (repeated across modules)

STRAW LAYER   STT MODULE   "RADIATOR"

Ar (gas)

C

(C3H6)n

**Dedicated carbon (graphite) target** to measure carbon background

**Radiator (CH2)** provides most of the detector mass with abundant hydrogen

# Measurement of Neutrino-Hydrogen in STT



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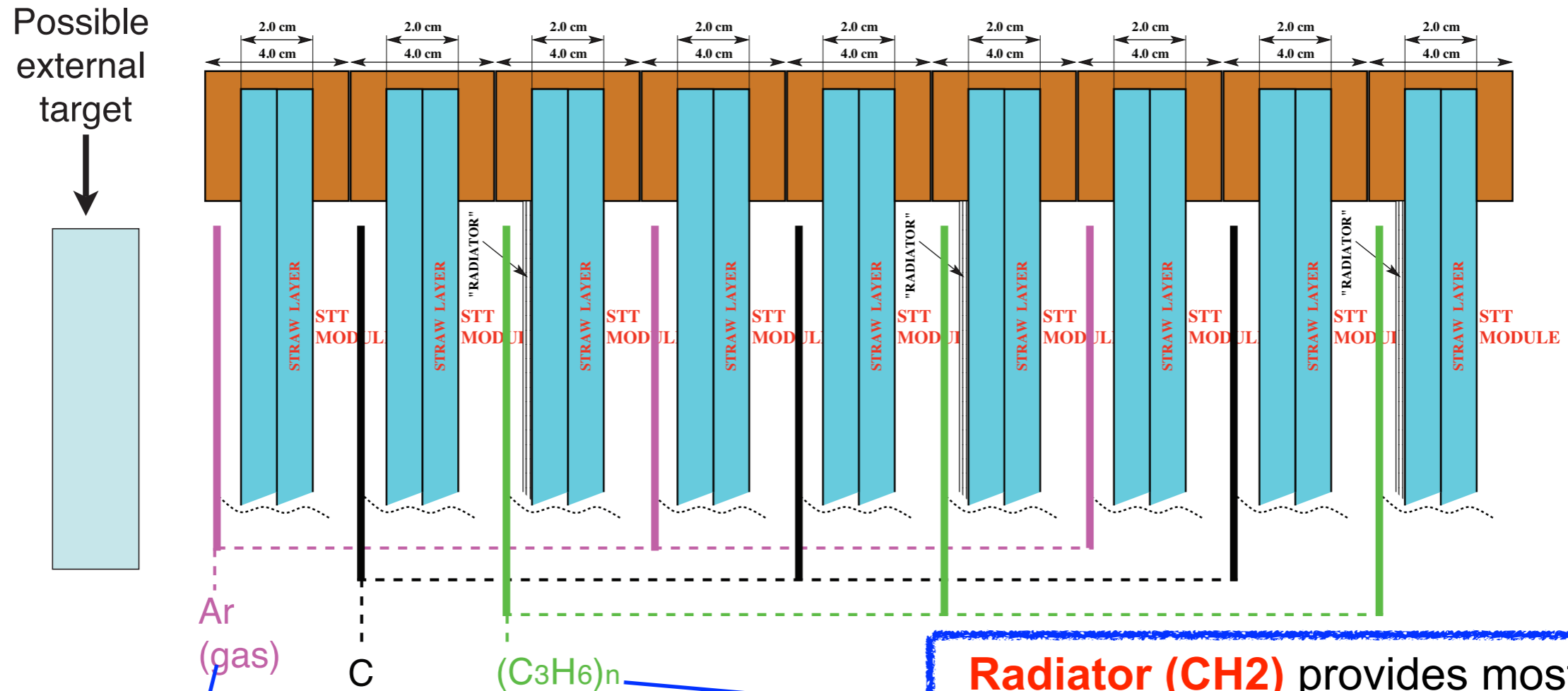STRAW LAYER
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**Ar** and other nuclear targets provide understanding of the **nuclear effects**

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**Ar** and other nuclear targets provide understanding of the **nuclear effects**

**arXiv:1809.08752, submitted to Nuclear Physics B**

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# Statistics

- Assuming 5-ton radiator (CH2) mass

| Process | CP optimized beam | | $\nu_\tau$ optimized beam | |
|---|---|---|---|---|
| | FHC 1.2MW, 5y | RHC 1.2MW, 5y | FHC 2.4MW, 2y | RHC 2.4MW, 2y |
| $\nu_\mu$ CC on $CH_2$ | 34,300,000 | 5,500,000 | 65,570,000 | 3,810,000 |
| $\bar{\nu}_\mu$ CC on $CH_2$ | 1,680,000 | 13,100,000 | 1,152,000 | 24,000,000 |
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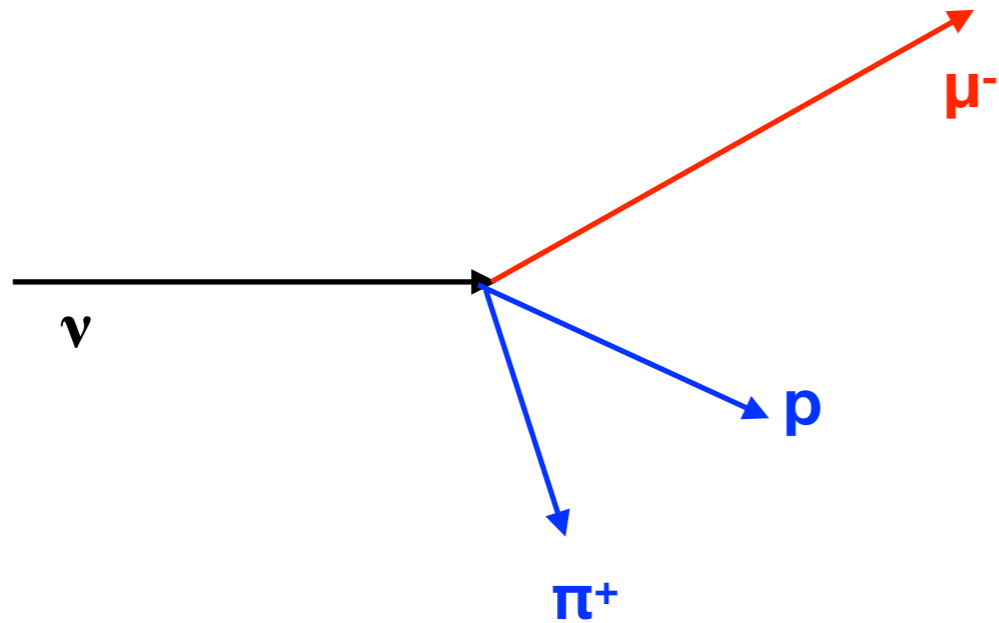
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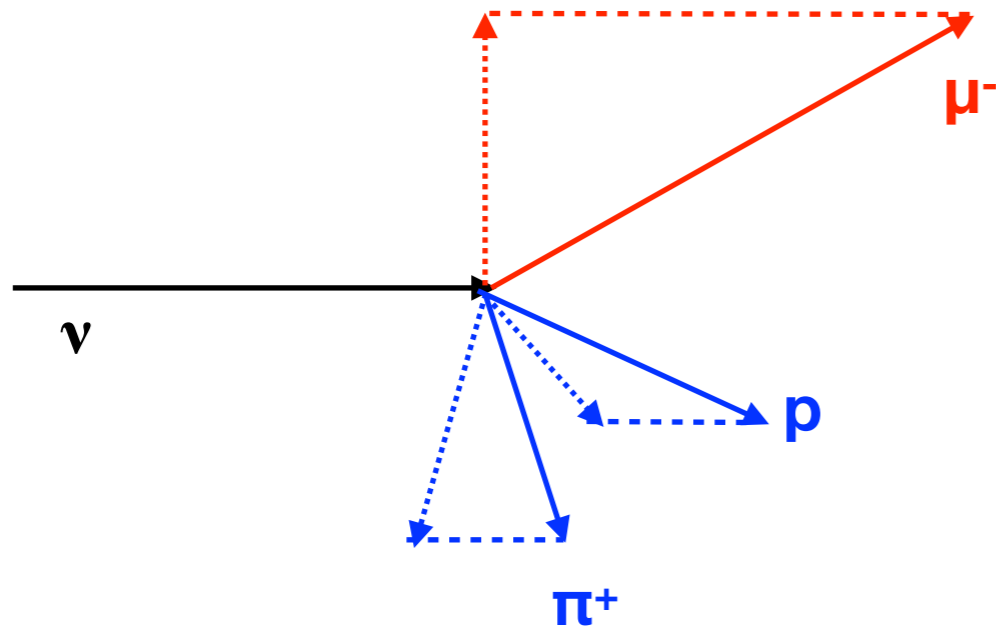**Large number of carbon background!**

**Excellent hydrogen statistics!**

- Do we need to subtract carbon events from CH2 in full phase space?
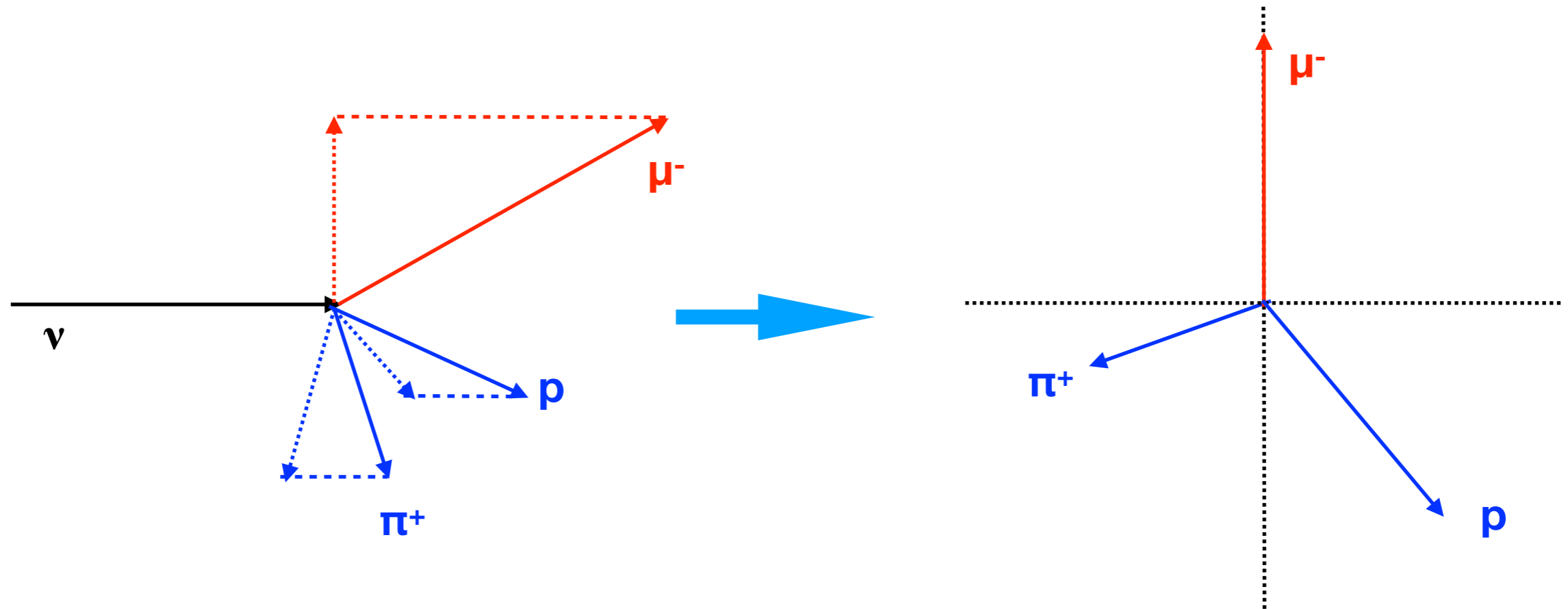
# $\nu$-H Selection: Transvers Kinematics



- **Hydrogen**: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.

- **Carbon**: Nuclear effects causes imbalance on the transverse plane.

- Key detector features: low-threshold, high resolution measurement of all final-state particles as much as possible.
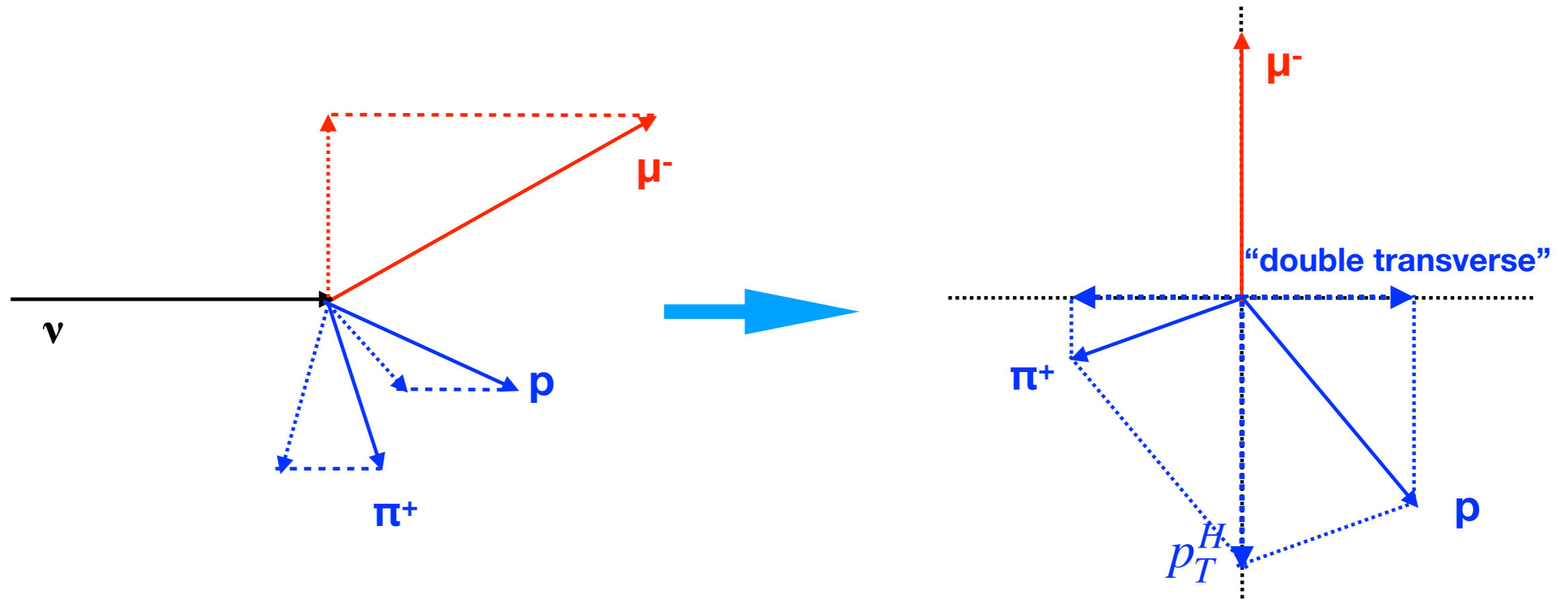
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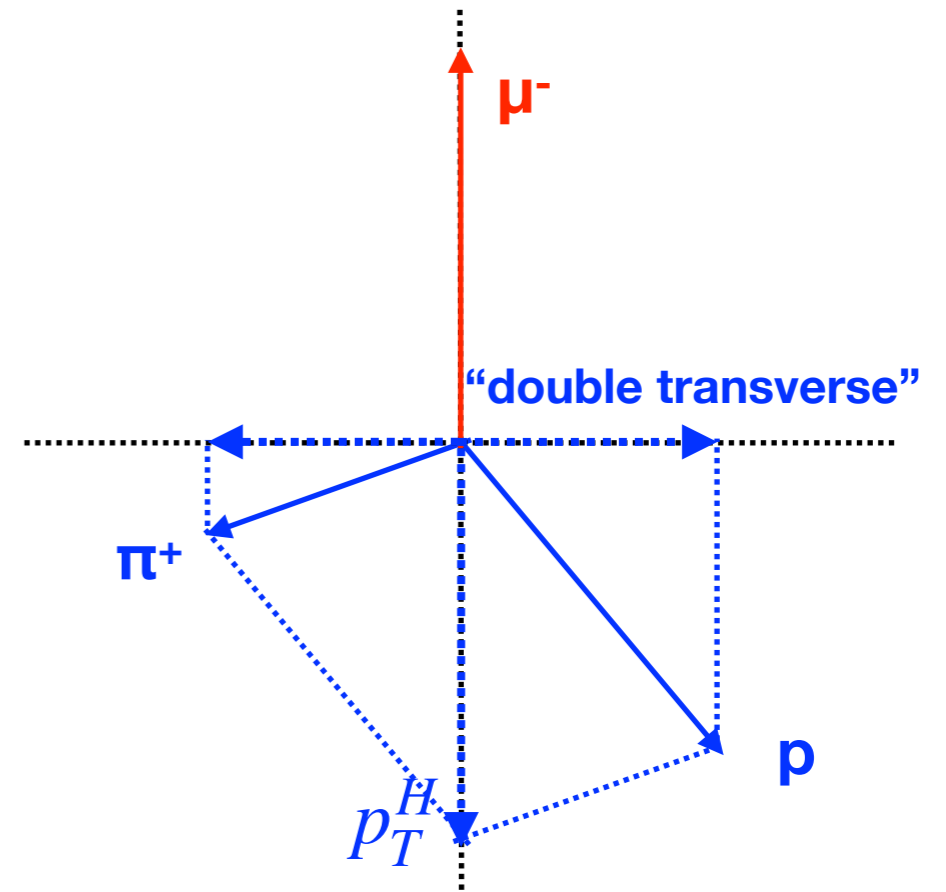
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X. Lu et al.: Phys. Rev. D 92, no. 5, 051302 (2015)

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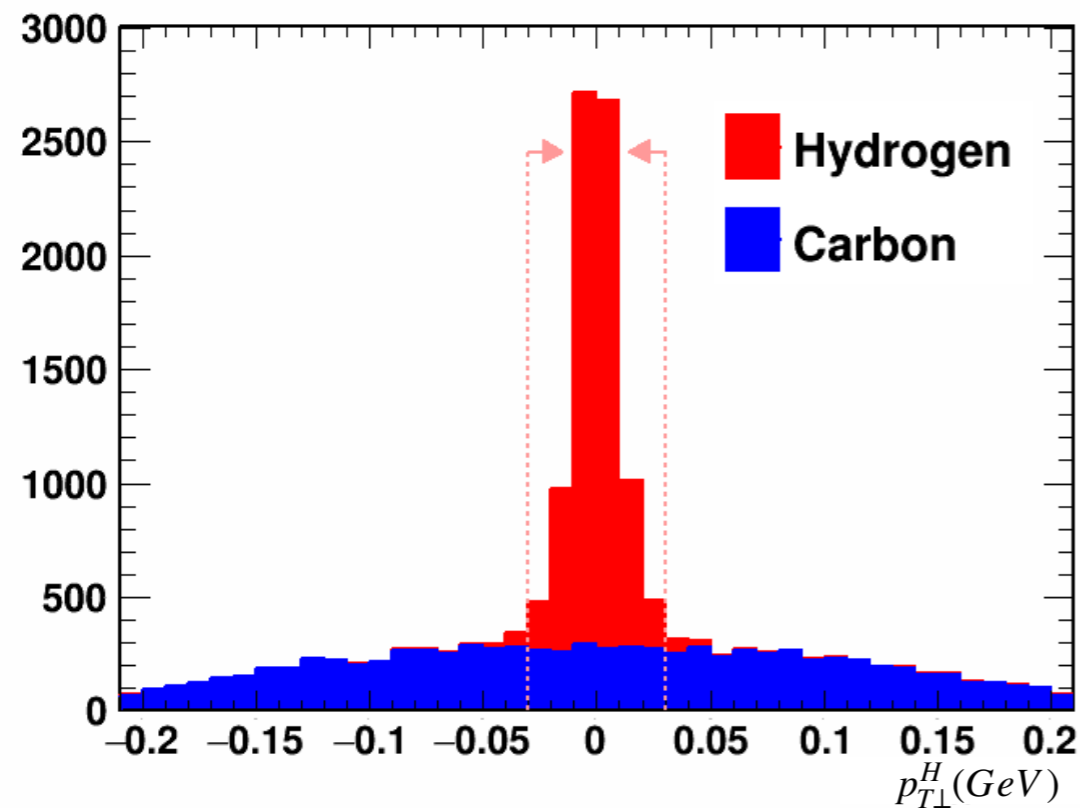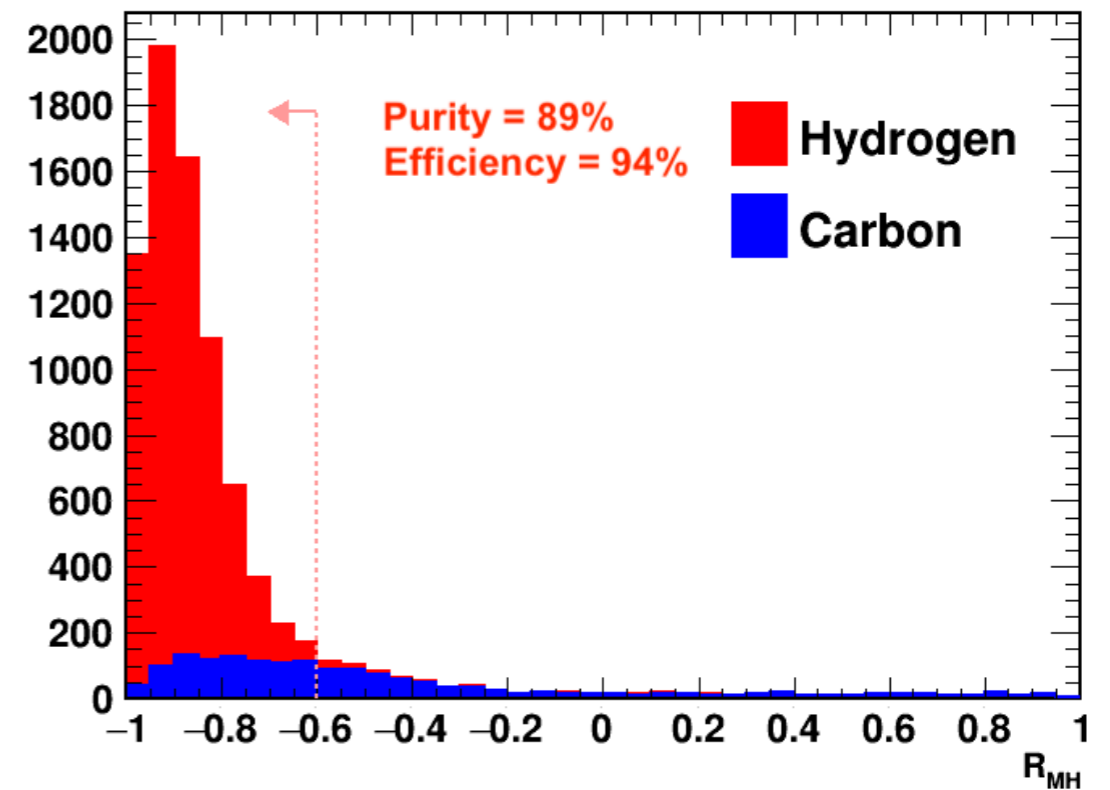
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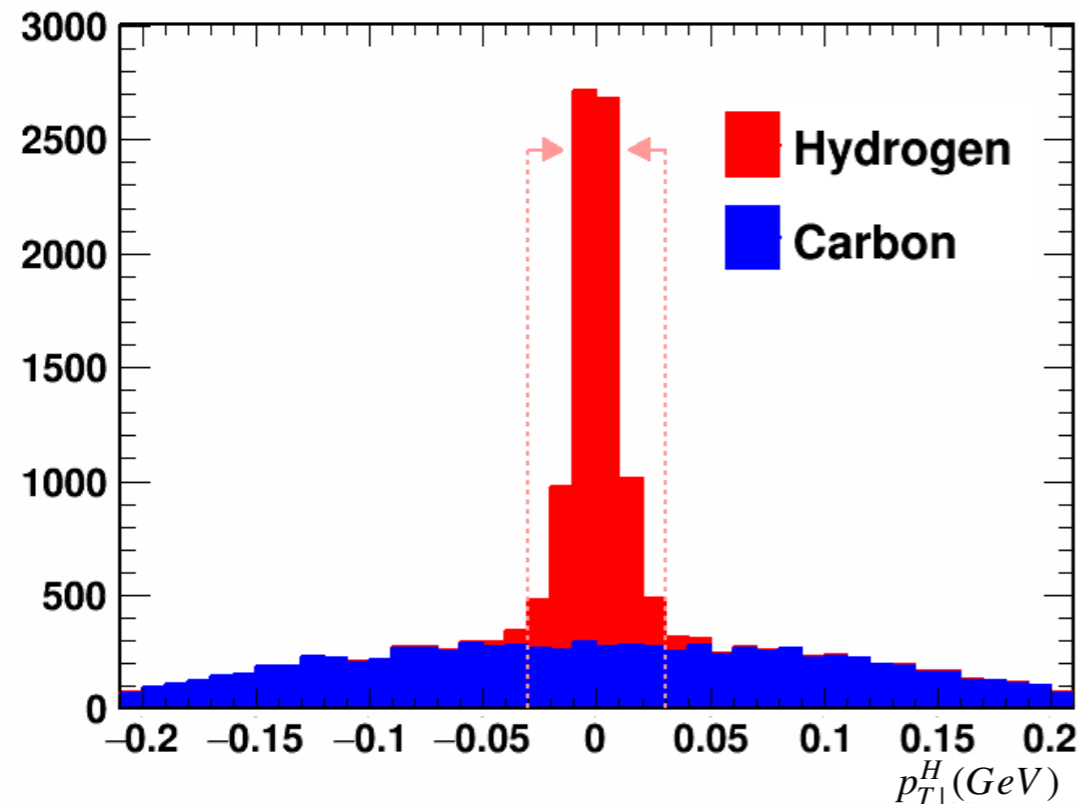


- Resonance pion production $\nu p \to \mu^- p \pi^+$

X. Lu et al.: Phys. Rev. D 92, no. 5, 051302 (2015)

- Two simple transverse variables:

  - $p_{T\perp}^H$ : momentum imbalance in the "double transverse" direction.

# $\nu$-H Selection: Resonance (3-Track Events)



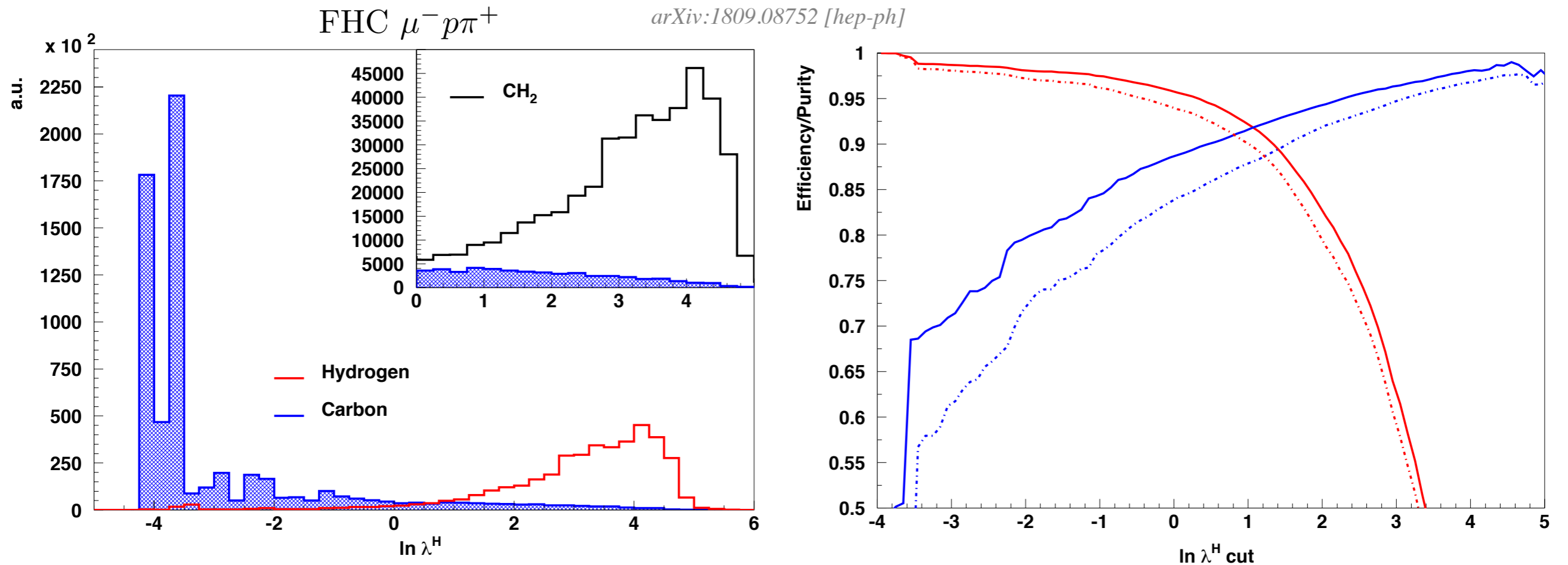- Resonance pion production $\nu p \to \mu^- p \pi^+$

- Two simple transverse variables:

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  - $R_{MH} = (P_T^M - P_T^H)/(P_T^M + P_T^H)$, where $p_T^M$ and $p_T^H$ are the missing $p_T$ and total $p_T$ of hadrons.

- **~90%** purity of hydrogen events (neutrino energy independent).

- The remaining carbon background is measured by the **graphite target**.

3. Distributions of ln $\lambda^H$ for the H signal, the C background and the CH$_2$ plastic (sum) for exclusive $\mu^- p\pi^+$ CC topologies. The multiple peaks are the effect of the binning used to build The H and C distributions are normalized to the expected relative abundance in CH$_2$.

ection. However, it provides information complementary to $R_{mH}$, so that the combined of both these variables improves the overall selection efficiency.

he use simple cuts $R_{mH} < -0.6$ and $p^H_{T} < 0.03$ GeV/c provides a clean $\to \mu^- p\pi^+$ H interactions from the CH$_2$ plastic with an efficiency of 93% and %, including non-resonant backgrounds as well as higher order resonances arly, we can select the equivalent $\nu$ topology with a purity of 84% ncy of 89%. Table summarizes the results of the kinematic selection.

e can further improve the selection or generalize it by using multivariate te ting the complete event kinematics [18–20]. Assuming the two momentum v pton and hadron system, we have in total 3 transverse and 2 longitudinal de m in the event selection, due to the invariance for an arbitrary rotation in the tr . Since we want to separate the same CC events with and without nuclear effects er assume that the overall reconstructed energy spectra are similar (up to the ring), thus somewhat reducing the rejection power of one of the longitudinal v result, we can define a complete kinematic set as 3 transverse plus one long bles. We select this latter as the angle between the total visible momentum ve cident neutrino direction (z-axis), $\theta_{\mu T}$. This variable is expected to be close interactions, up to the tiny beam divergence, while it is much larger in inte ated from nuclear targets.

e use a likelihood function incorporating multi-dimensional correlations among kinematic bles. An optimization of the kinematic selection suggests the following function:

$$\mathcal{L}^H = \mathcal{L}^H[R_{mH}, p^H_T, \theta_{\mu T}, p^m_T, \Phi_{pH}] \tag{1}$$

the the square bracket denotes ellipses (Fig. 2) I the H function is over constrained e transverse plane to compensate for the missing correlations, binning, etc. A function
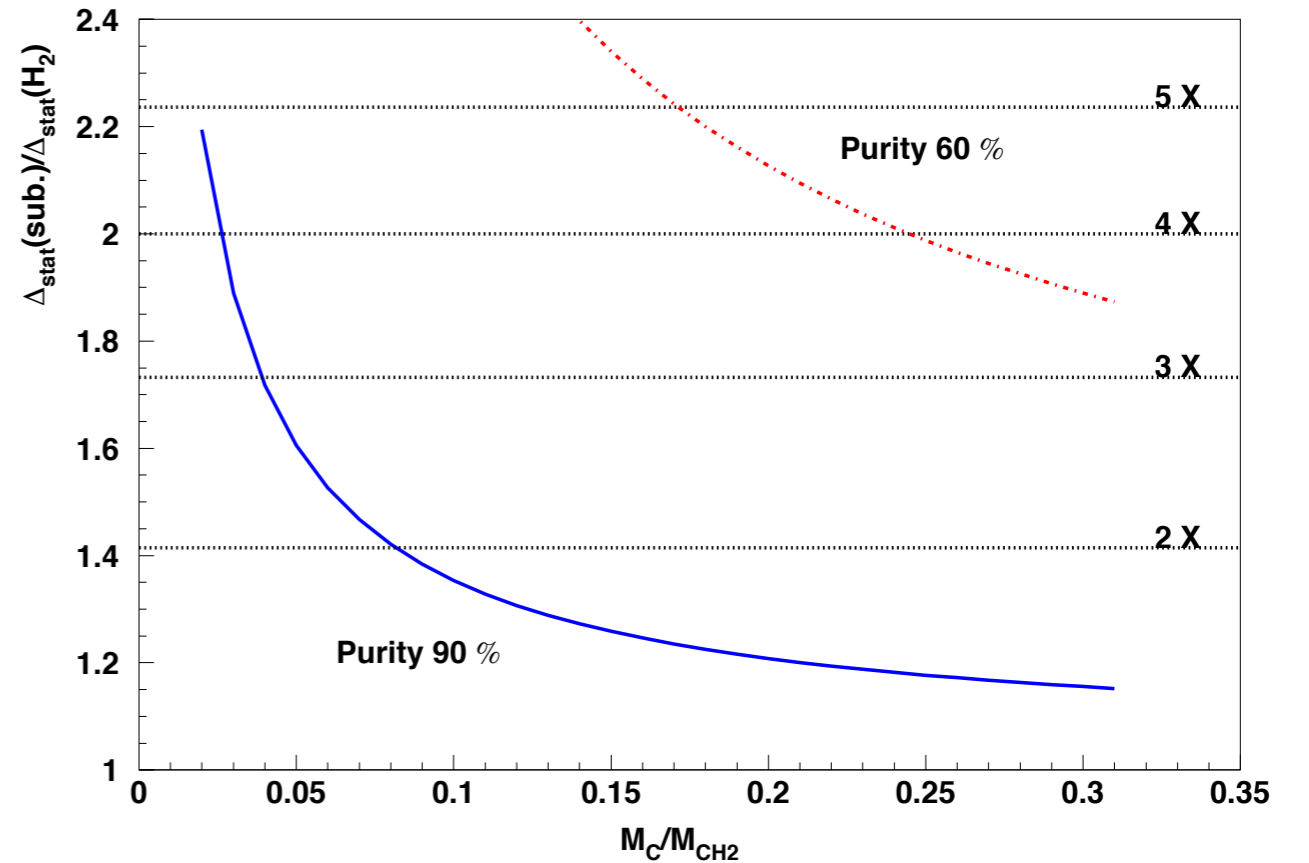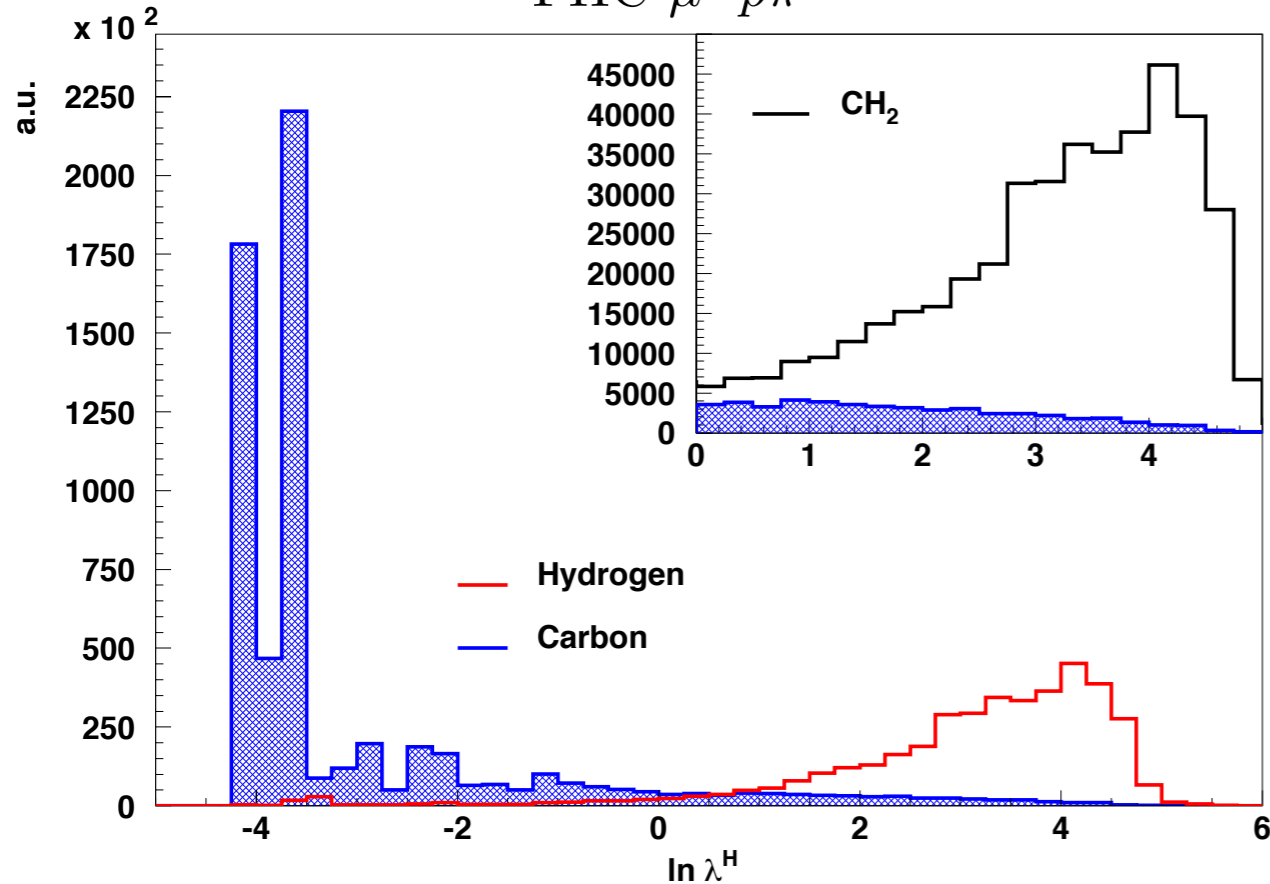


R. Petti
University of South Carolina

- **Build log likelihood function using more variables ($R_{MH}, p^M_T, p_{12}, \phi_{OH}, \theta_{\mu T}$) can achieve even better purity while maintains efficiency.**

*LBNE Near Detector Workshop*
*Columbia, December 2, 2010*

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USC

**Roberto Petti**

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## HiResMν:
### Costs and Detector Design

R. Petti
University of South Carolina

arXiv:1809.08752 [hep-ph]

| Process | GH₂ target | H target | CH₂ selected | C bkgnd |
|---|---|---|---|---|
| $\nu_\mu$ CC $\mu^- p\pi^+$ | 53,824,000 | 2,484,000 | 2,430,000 | 194,000 |
| $\nu_\mu$ CC inclusive | 34,900,000 | 3,591,000 | 4,140,000 | 1,160,000 |
| $\bar\nu_\mu$ CC $\mu^+ p\pi^-$ | 836,000 | 373,000 | 365,000 | 29,100 |
| $\bar\nu_\mu$ CC $\mu^+ n$ | 4,960,000 | 1,240,000 | 360,000 | 70,000 |
| | | | 648,000 | 126,000 |
| $\bar\nu_\mu$ CC inclusive | 13,000,000 | 2,882,000 | | |

Achievable statistics

Purity 90 %
Purity 60 %

$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C}$$

LBNE Near Detector Workshop
Columbia SC, December 12, 2009

- The subtraction of carbon background by the **graphite target** is totally data-driven, model-independent.

$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_{C/CH_2}}{M_C}$$

LBNE Near Detector Workshop

- Optimizing graphite mass to minimize statistical uncertainty.

Columbia SC, December 12, 2009

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# HiResM$\nu$:
# Costs and Detector Design

| Process | $R_{mH}$ and $p_{T\perp}^H$ cuts | | $\ln \lambda^H$ cut | |
|---|---|---|---|---|
| | Efficiency | Purity | Efficiency | Purity |
| $\nu_\mu p \to \mu^- p\pi^+$ | 93% | 86% | 90% | 92% |
| $\bar{\nu}_\mu p \to \mu^+ p\pi^-$ | 89% | 84% | 90% | 88% |
| $\bar{\nu}_\mu p \to \mu^+ n$ | 95% | 80% | | |
| $\nu_\mu p$ CC inclusive | 83% | 73% | | |

R. Petti

*University of South Carolina*

- Various channels studied with simple cuts and LH.

- Working on improvements.

# $\nu$-H Selection: $\bar{\nu}_\mu$- CCQE
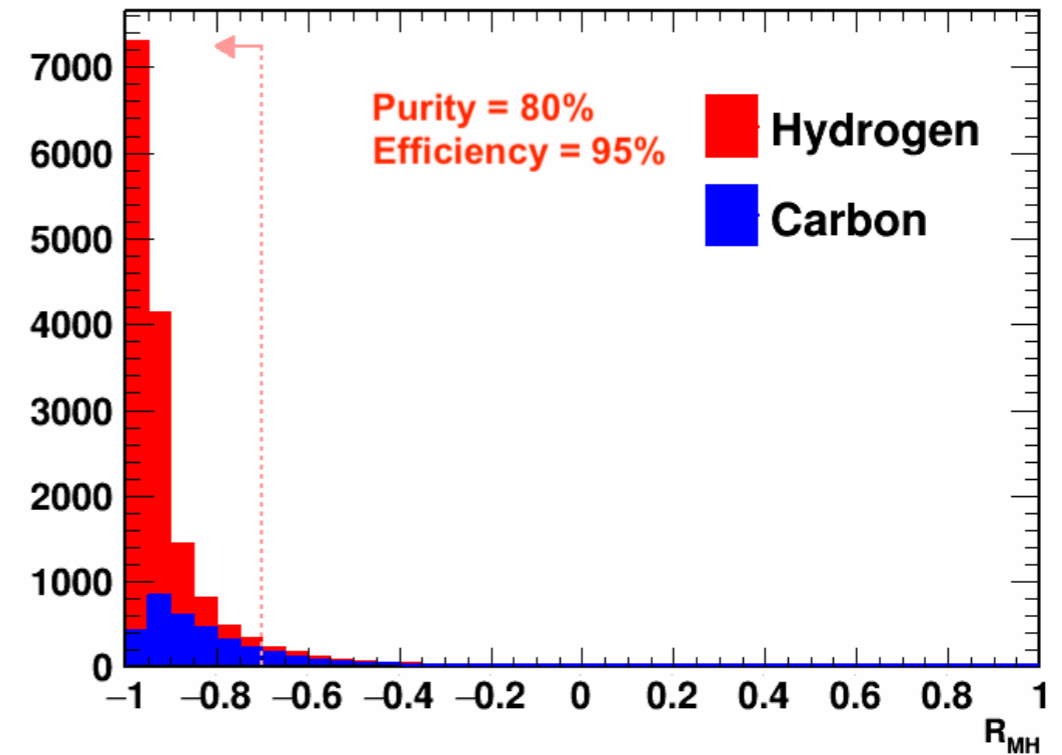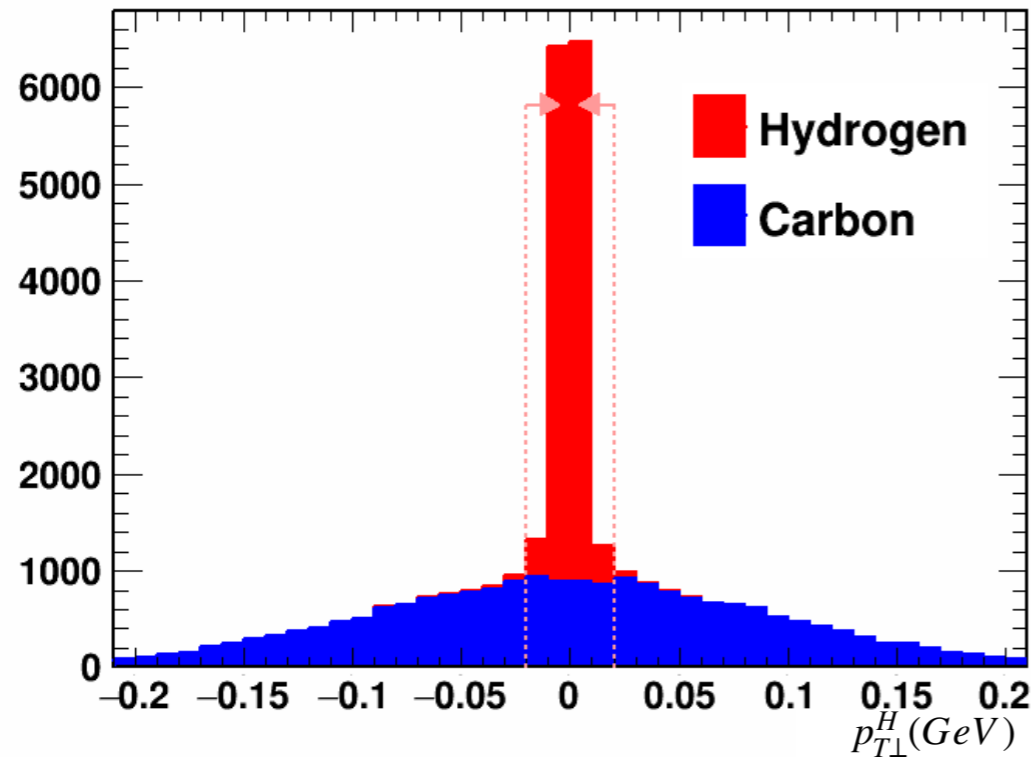


- Anti-neutrino QE: $\bar{\nu}_\mu p \to \mu^+ n$

- About 25% of the neutrons interact within STT producing charged secondary particles. Can be greatly improved if considering ECAL.

- Interaction vertex position is obtained from the muon.

- Get the neutron direction from the vertex to interaction point.

- Get the neutron energy from the muon kinematics with QE assumption.

# Neutrino Energy Reconstruction
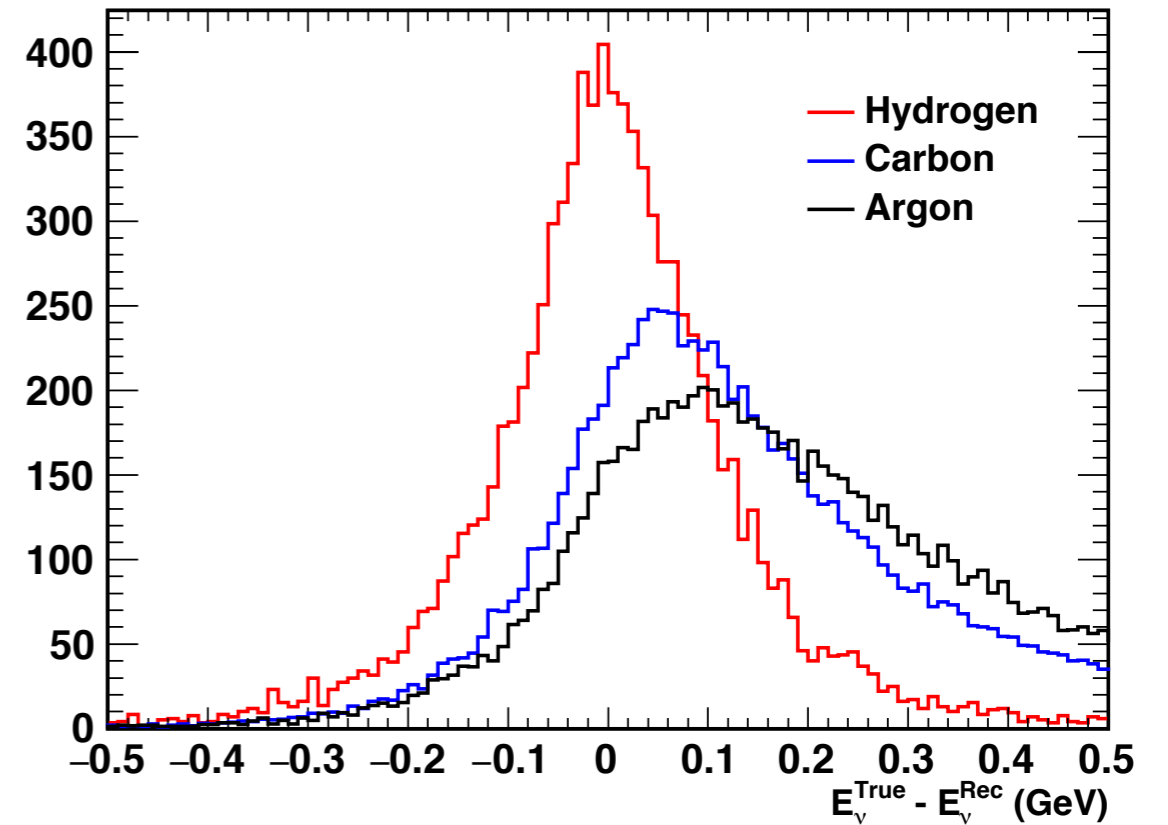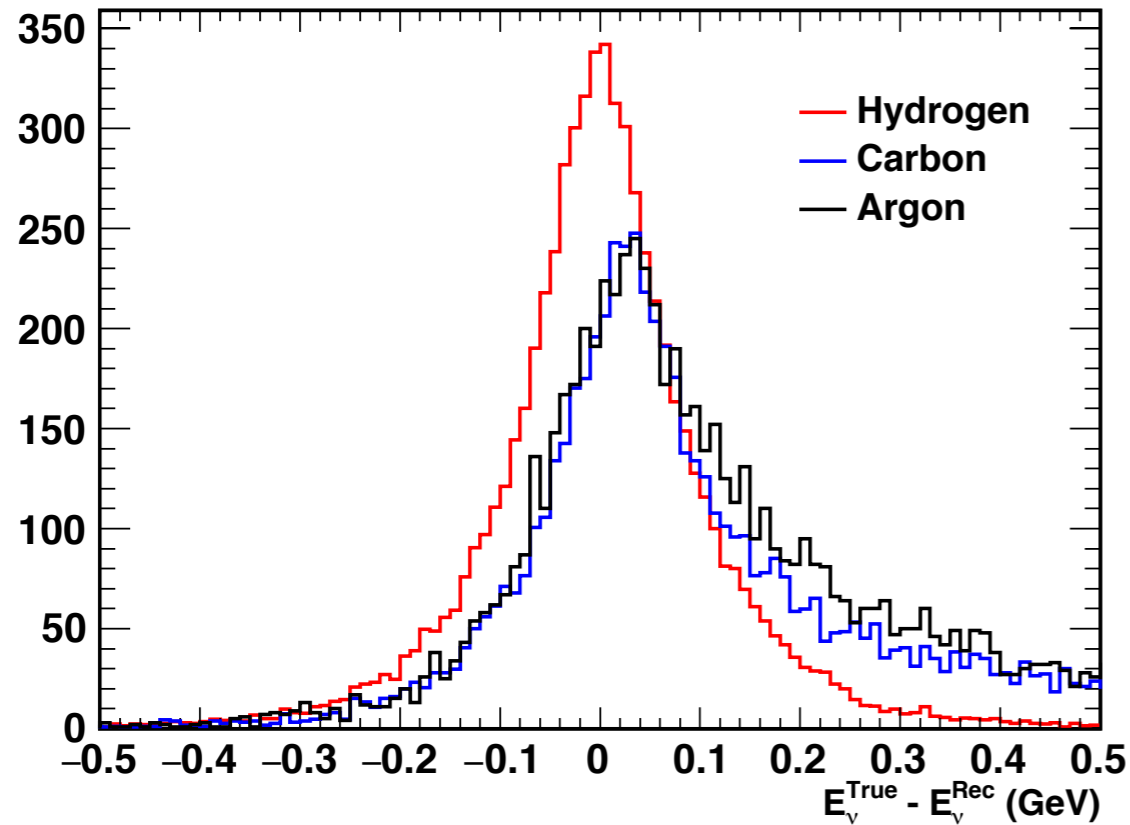


- Hydrogen shape is free from nuclear effects (detector smearing only).
- The shapes of nuclear targets are model-dependent.

# Nuclear Effects
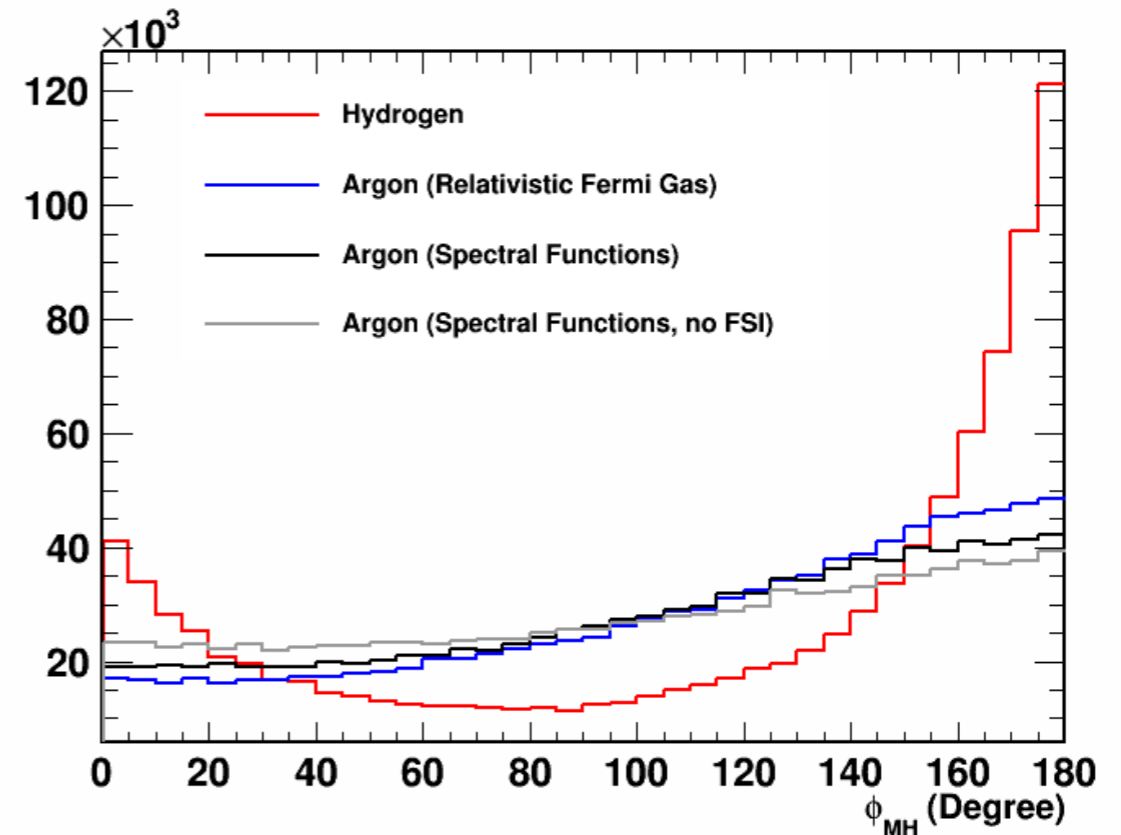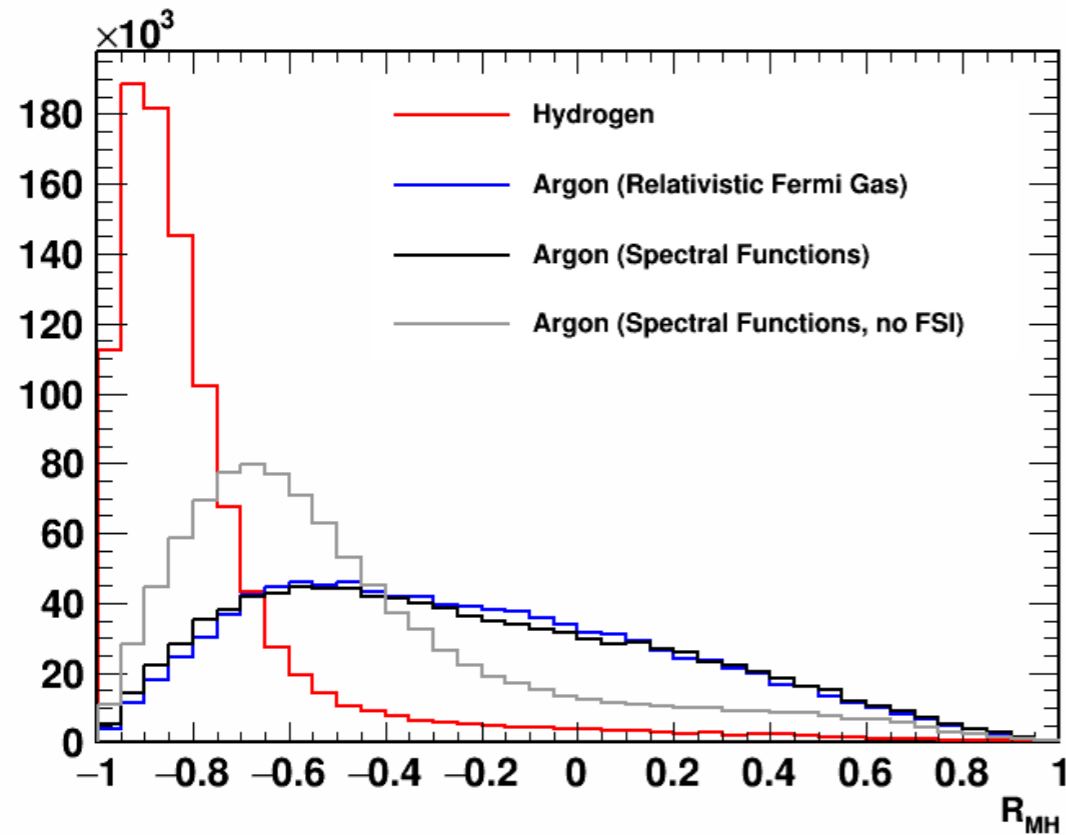


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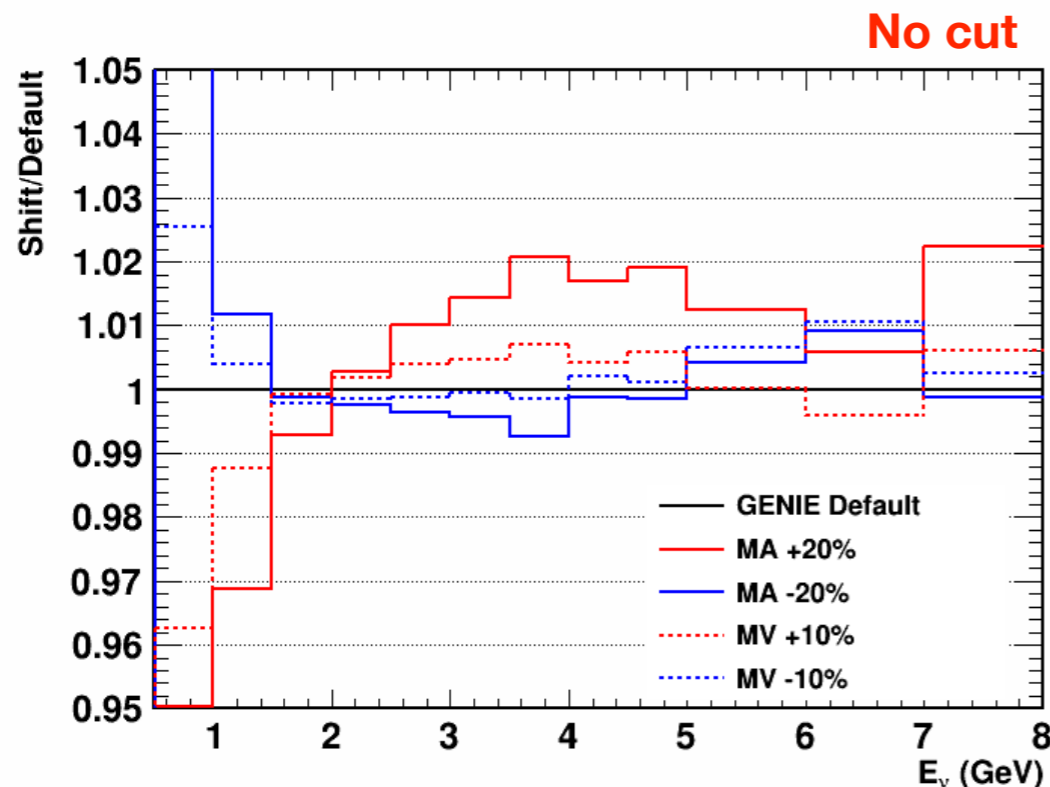- The shapes of nuclear targets are model-dependent.

# Flux Measurements: Low-ν Method

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \, \boxed{\Phi(E_\nu)} P_{osc}(E_\nu) \sigma(E_\nu) R_{det}(E_{rec}, E_\nu)$$

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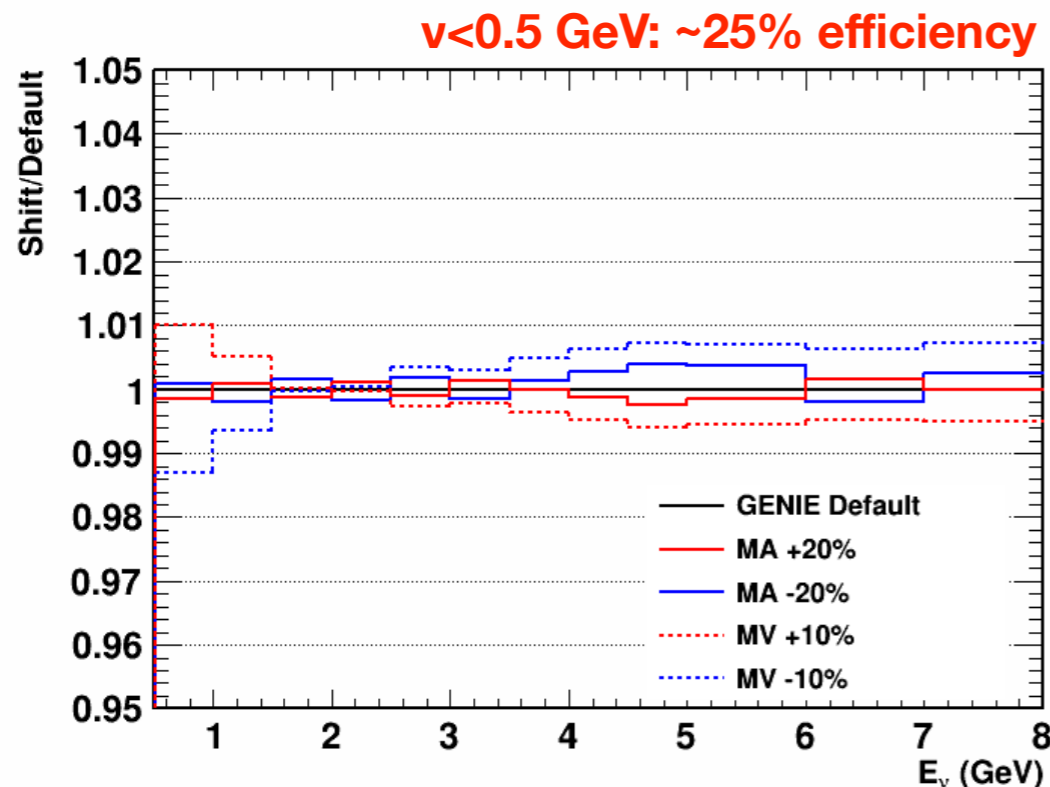**Need a process with small cross-section uncertainty**

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- Cross section is flat at low $\nu = E_\nu - E_\mu$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).

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- The cross-sections of $\nu$-H are better understood than heavy nucleus and <u>free from uncertainties from nuclear effects</u>.

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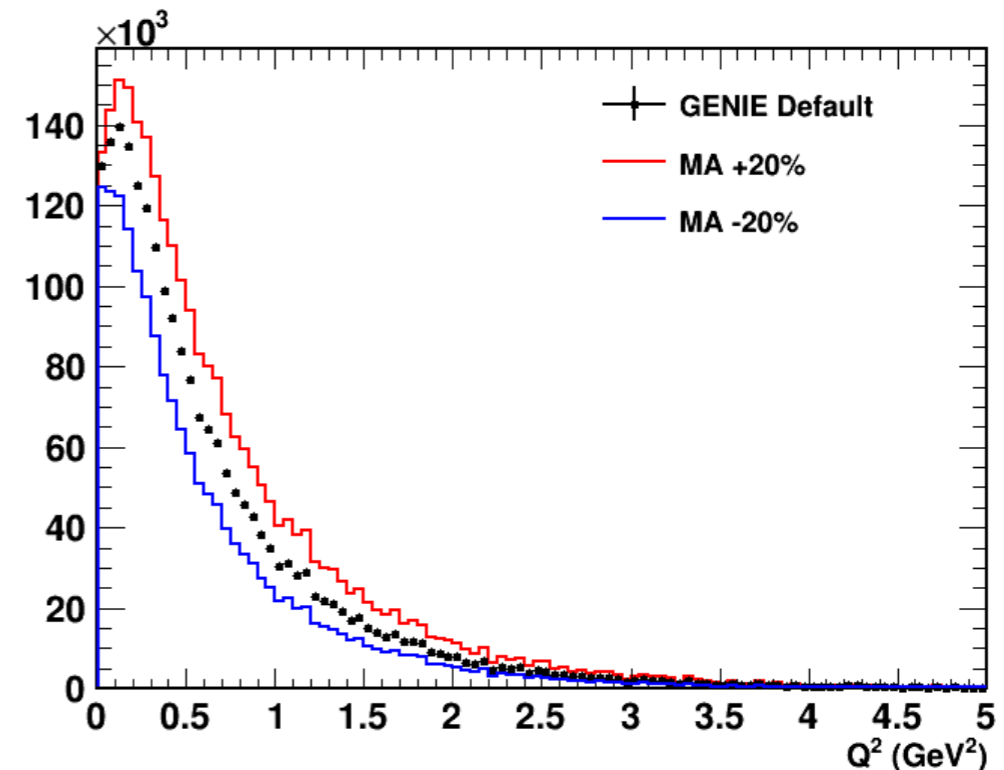
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**No cut**

# Flux Measurements: Low-$\nu$ Method

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \boxed{\Phi(E_\nu)} P_{osc}(E_\nu) \boxed{\sigma(E_\nu)} R_{det}(E_{rec}, E_\nu)$$

**Need a process with small cross-section uncertainty**

**Nuclear effects!**

- Cross section is flat at low $\boxed{\nu = E_\nu - E_\mu}$ with smaller uncertainty: flux shape measurement (used by NOMAD, MINOS, MINERvA).

- The cross-sections of $\nu$-H are better understood than heavy nucleus and <u>free from uncertainties from nuclear effects</u>.

**$\nu$<0.5 GeV: ~25% efficiency**



**Cross-section uncertainty < 1%**

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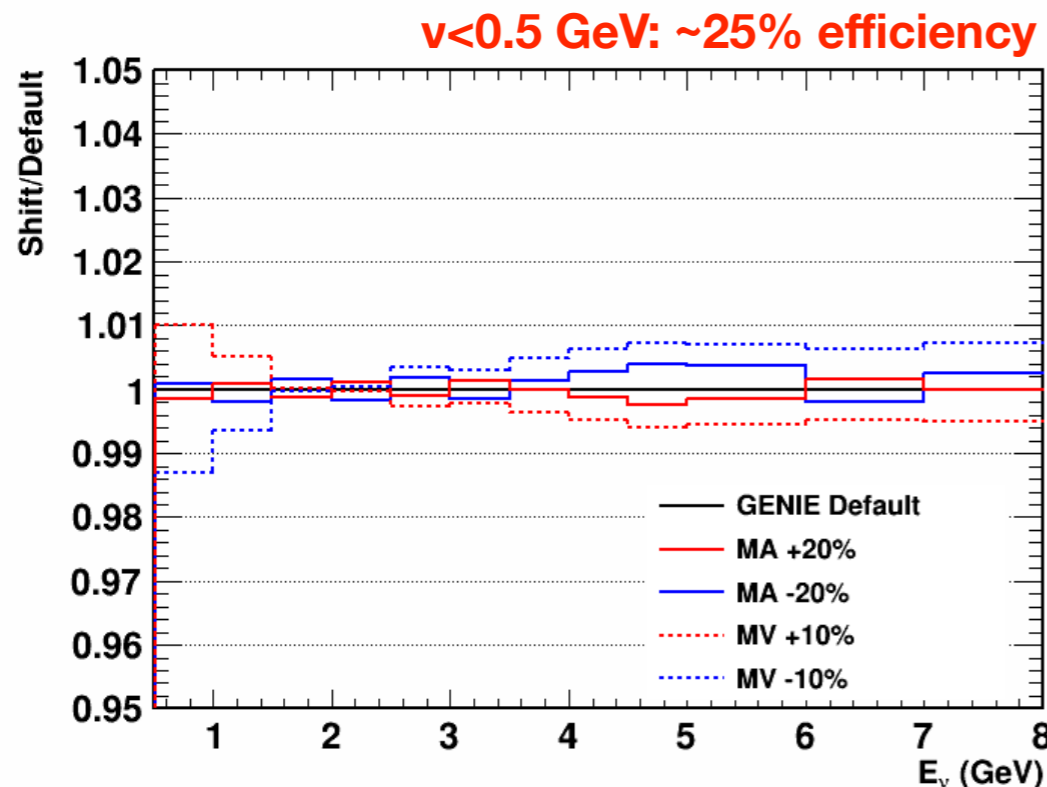


**Cross-section uncertainty < 1%**

**Uncertainties further constrained by differential measurements in inclusive sample.**

# Flux Measurements: $\bar{\nu}_\mu$-CCQE

$$\frac{d\sigma}{dQ^2}\Big|_{Q^2=0} = \frac{G_F^2 \cos^2\theta_c}{2\pi}\left[F_1^2(0) + G_A^2(0)\right]$$

- Measuring neutrons at a distance from vertex allows measurement of very low $Q^2$

- At $Q^2 \Rightarrow 0$, the QE cross section of free proton is known to $< 1\%$ from measurements of neutron decay.

- Good f

**RHC $\bar{\nu}_\mu p \rightarrow \mu^+ n$**

Purity = 80%
Efficiency = 95%

■ Hydrogen

■ Carbon

7000

6000

5000

4000

3000

# Can we measure $\nu$-H in an alternative way?

- A pure-hydrogen detector with comparable statistics causes safety concerns, and can be potentially expensive.

  - Fill Argon-Gas TPC with hydrogen would also reduce $\nu$-Ar statistics.

- 3DST (CH target) has smaller (1/2) number of hydrogen and poorer resolution.

  - Larger statistical uncertainty.

  - Lower efficiency.

  - Higher background level makes subtraction difficult.

  - No dedicated carbon targets (with same detector response as CH) to constrain background systematics.

# Summary

- We propose to measure $\nu$-H in the STT detector by statistically subtracting C from CH2.

  - Large statistics.

  - Subtraction is data-driven.

  - Safe, and cheap.

- Lots of benefits to DUNE

  - Neutrino energy scale free from nuclear effects.

  - Measure/constrain nuclear effects.

  - Flux measurement.

  - Cross-section physics.

- Complementary to other ND measurements.

# Back up slides

# Straw Tube Track



Muon Detector

ECAL

Dipole B

Straw Tube Tracker (Argon target)
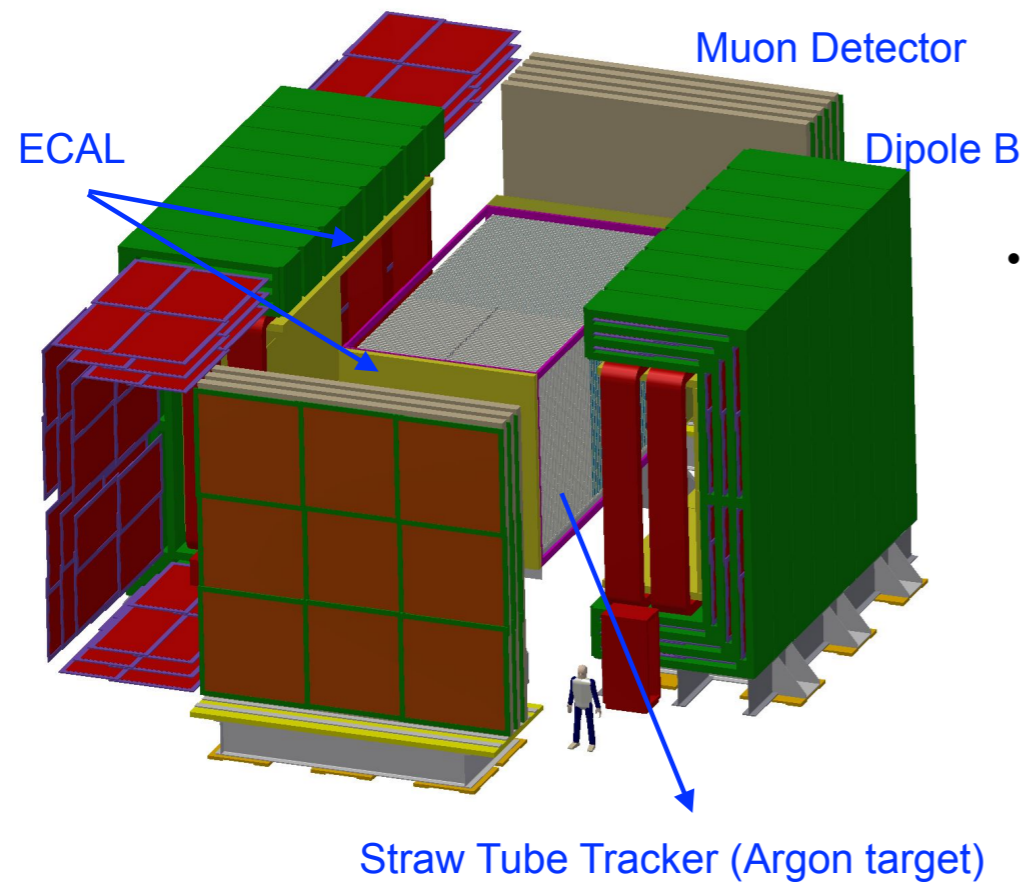
| Radiator (Target) Mass | 7 tons |
|---|---|
| Other Nuclear Target Mass | 1–2 tons |
| Vertex Resolution | 0.1 mm |
| Angular Resolution | 2 mrad |
| $E_e$ Resolution | $6\%/\sqrt{E}$ ( 4% at 3 GeV) |
| $E_\mu$ Resolution | 3.5% |
| $\nu_\mu/\bar{\nu}_\mu$ ID | Yes |
| $\nu_e/\bar{\nu}_e$ ID | Yes |
| $\pi^-$ .vs. $\pi^+$ ID | Yes |
| $\pi^+$ .vs. $proton$ .vs. $K^+$ | Yes |
| $NC\pi^0$/CCe Rejection | 0.1% |
| $NC\gamma$/CCe Rejection | 0.2% |
| $CC\mu$/CCe Rejection | 0.01% |

- • $\sim$3.5m×3.5m×6.5m, $\rho\approx$0.1 g/cm$^3$, $X_0\approx$6m.

- Magnetic field for charge and momentum measurement.

- $4\pi$ ECAL coverage.

- $4\pi$ MuID (RPC) in dipole and up/downstream.

- Multiple nuclear targets:
  Pressurized $^{40}$**Ar** target ($\approx$×69 FD-stat), & $^{40}$**Ca, C**  (~×220 FD-stat).

# Nu-H Selection: Transvers Kinematics
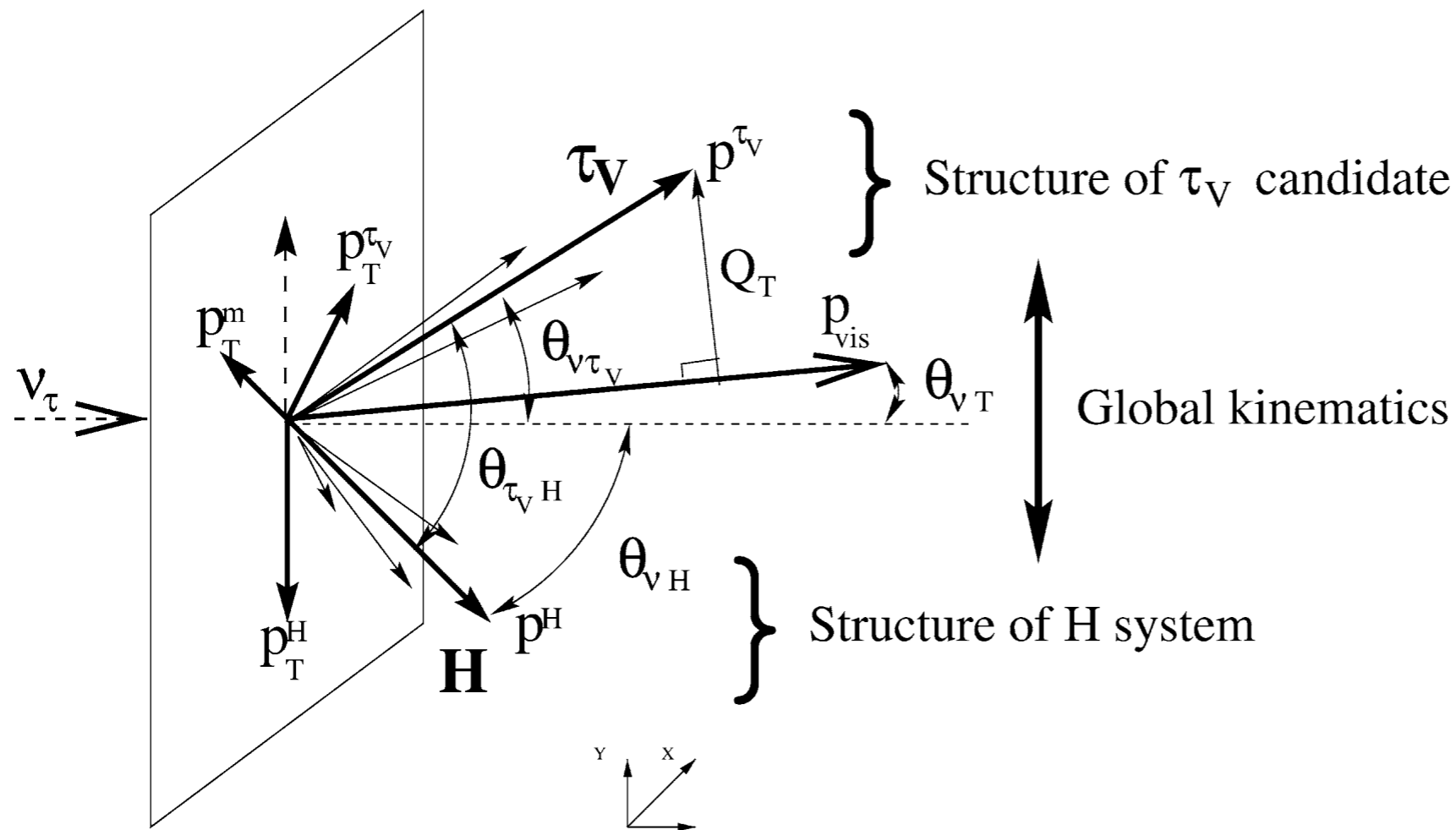


- **Hydrogen**: Momentums of final-state particles are balanced in the direction transverse to the beam direction without nuclear effects. The only smearing is detector effects.

- **Carbon**: Nuclear effects causes imbalance on the transverse plane.

- Key detector features: low-threshold, high resolution measurement of all final-state particles as much as possible.

# Anti-Neutrino Mode: 3trk

# Generator Comparisons

## HiResMν:
## Costs and Detector Design
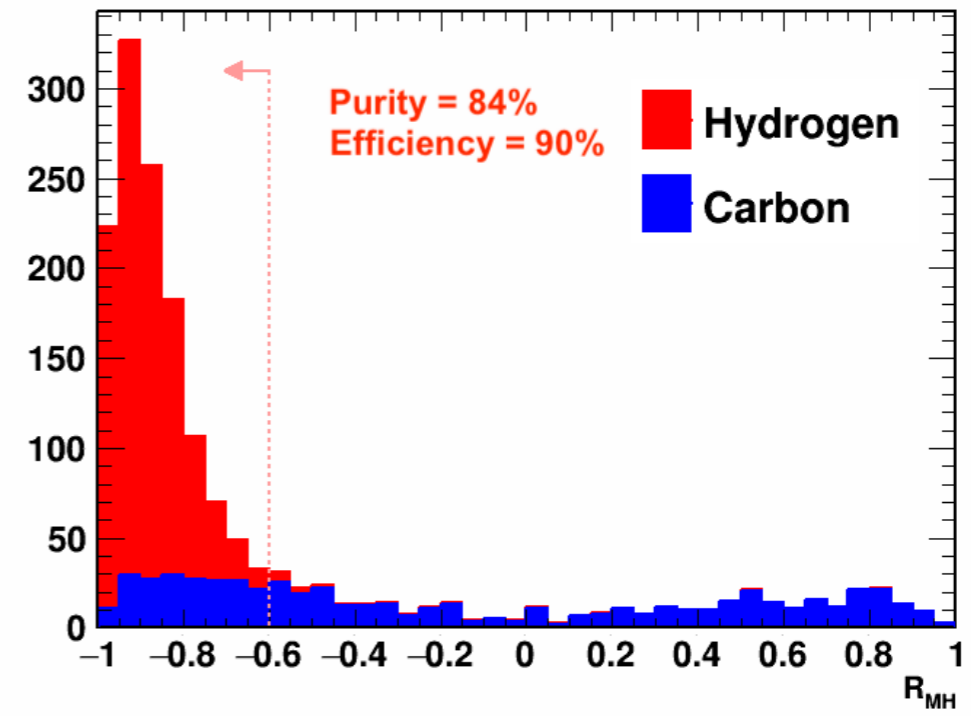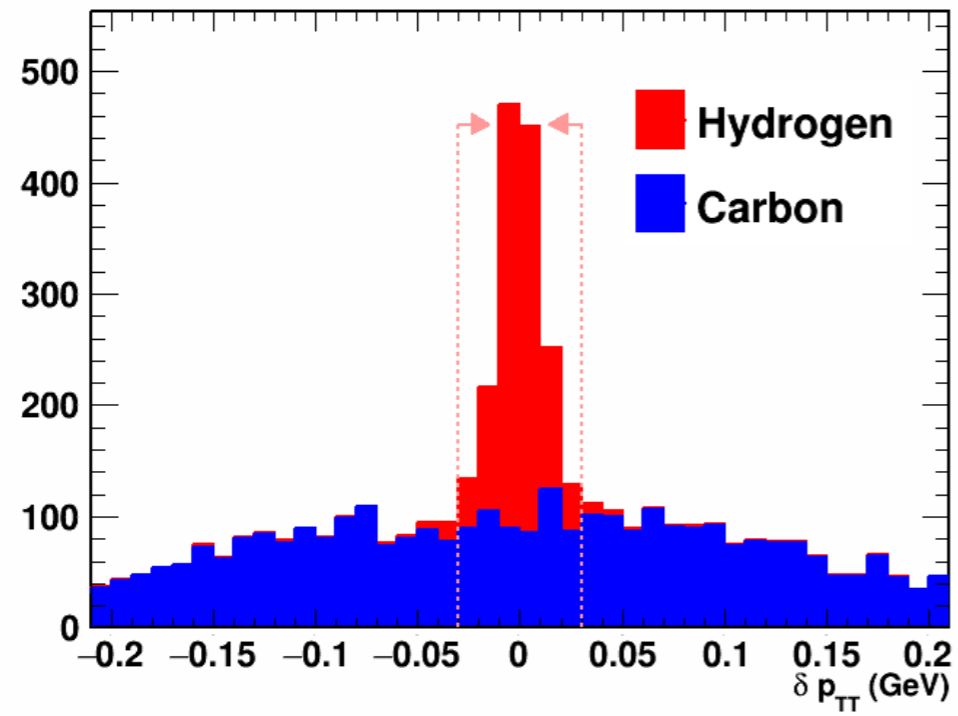
| Process | NuWro | | GiBUU | | GENIE | |
|---|---|---|---|---|---|---|
| | Efficiency | Purity | Efficiency | Purity | Efficiency | Purity |
| $\nu_\mu p \to \mu^- p \pi^+$ | 93% | 86% | 93% | 84% | 93% | 91% |
| $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ | 89% | 84% | 89% | 87% | 89% | 89% |

TABLE III. Comparison of the efficiency and purity for the kinematic selection of H interactions from the $CH_2$ plastic target using simple cuts on $R_{mH}$ and $p^H_{T\perp}$ with the NuWro [21], GiBUU [22], and GENIE [23] event generators. The same selection cuts as in Tab. I are used in all cases.

R. Petti

*University of South Carolina*

**This is to show that the number of efficiencies and purities we estimate is realistic.
the difference between generators here will not be systematics because we will have carbon data to measure them**
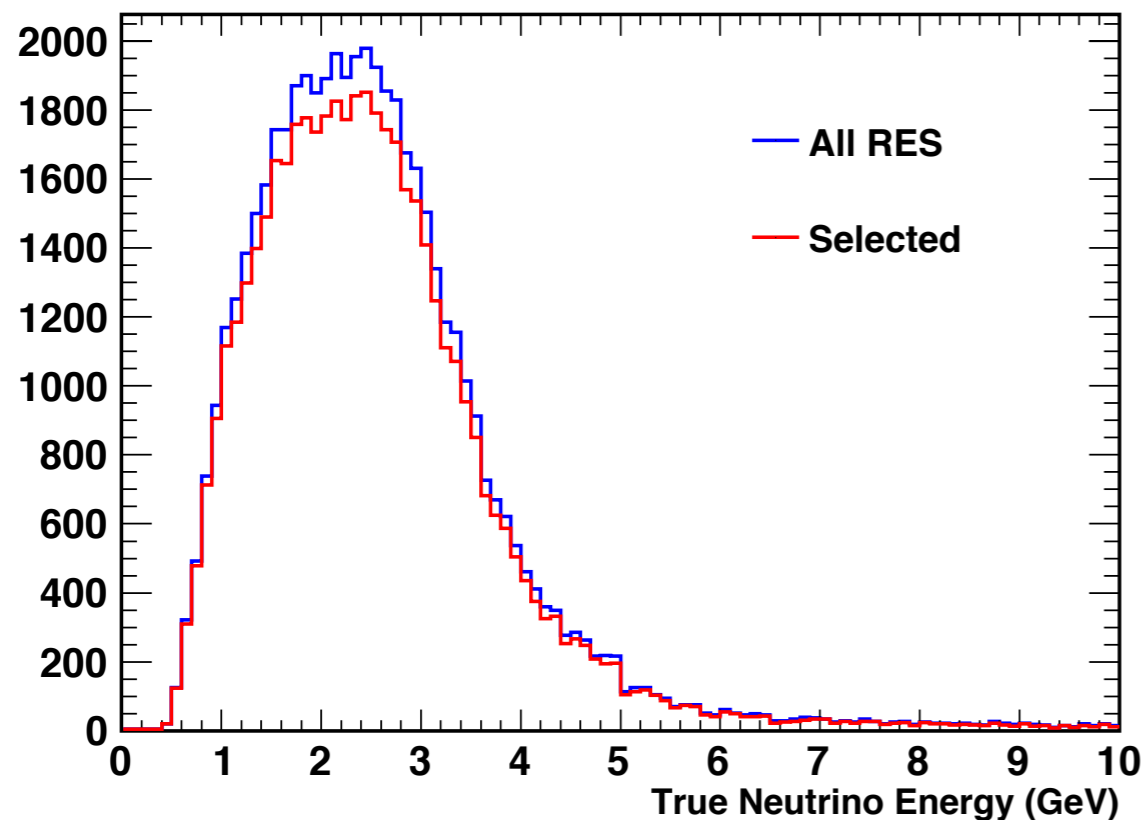
*LBNE Near Detector Workshop*

*Columbia SC, December 12, 2009*

# Background Shape

**Prediction by different models for C12**
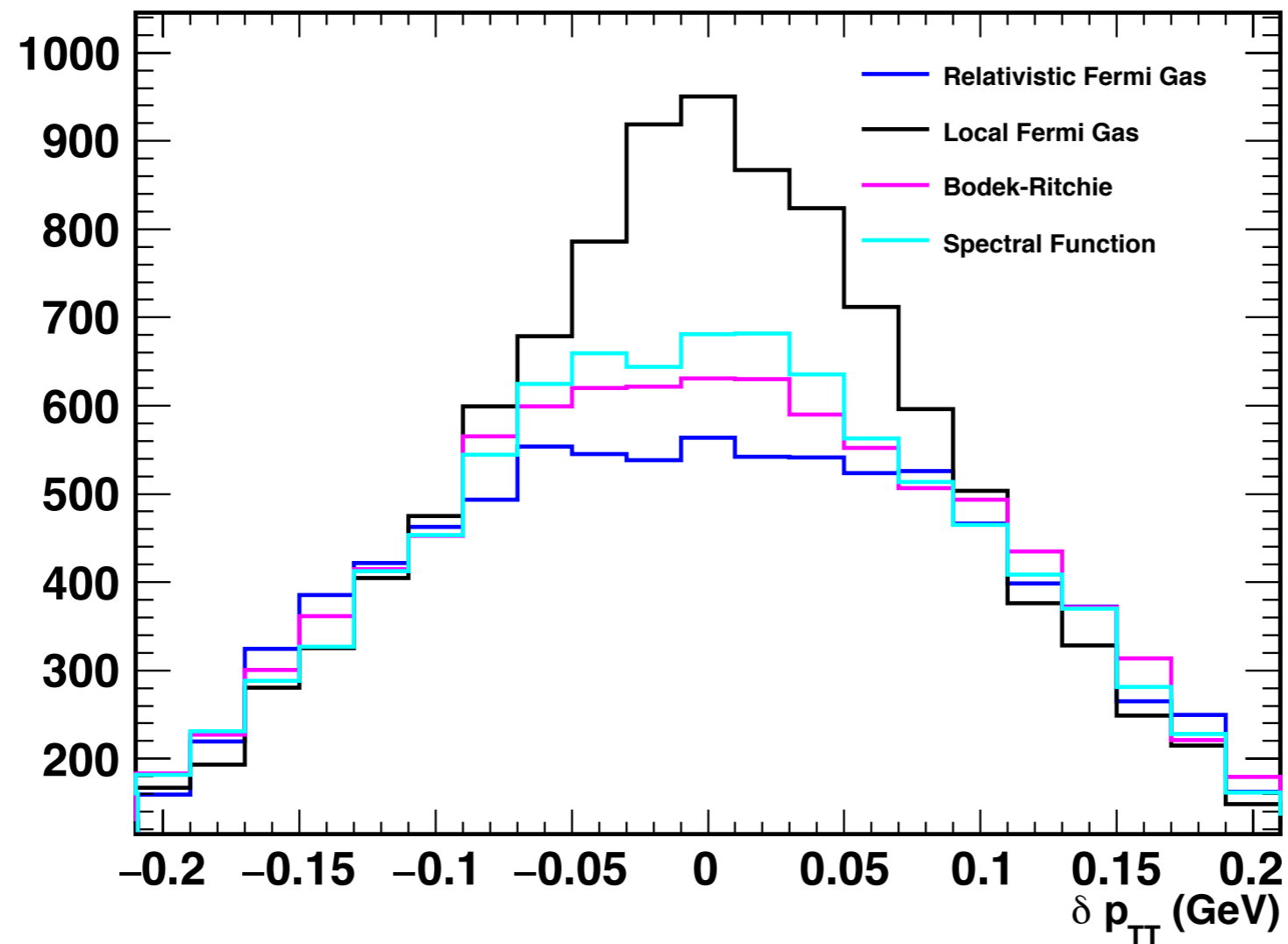


Models differ in prediction of background shape:
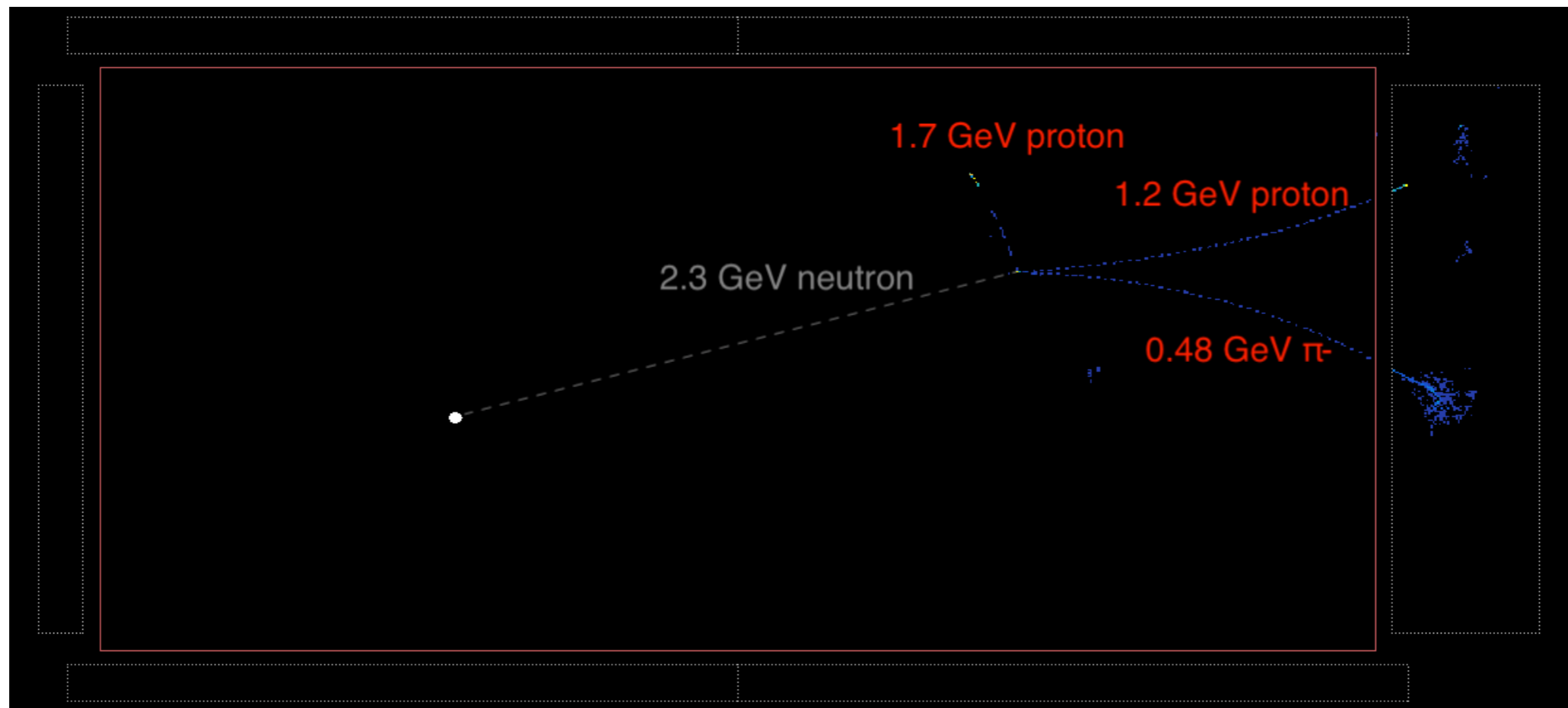We must have carbon data to measure it!

# Nu-H Selection: Efficiency
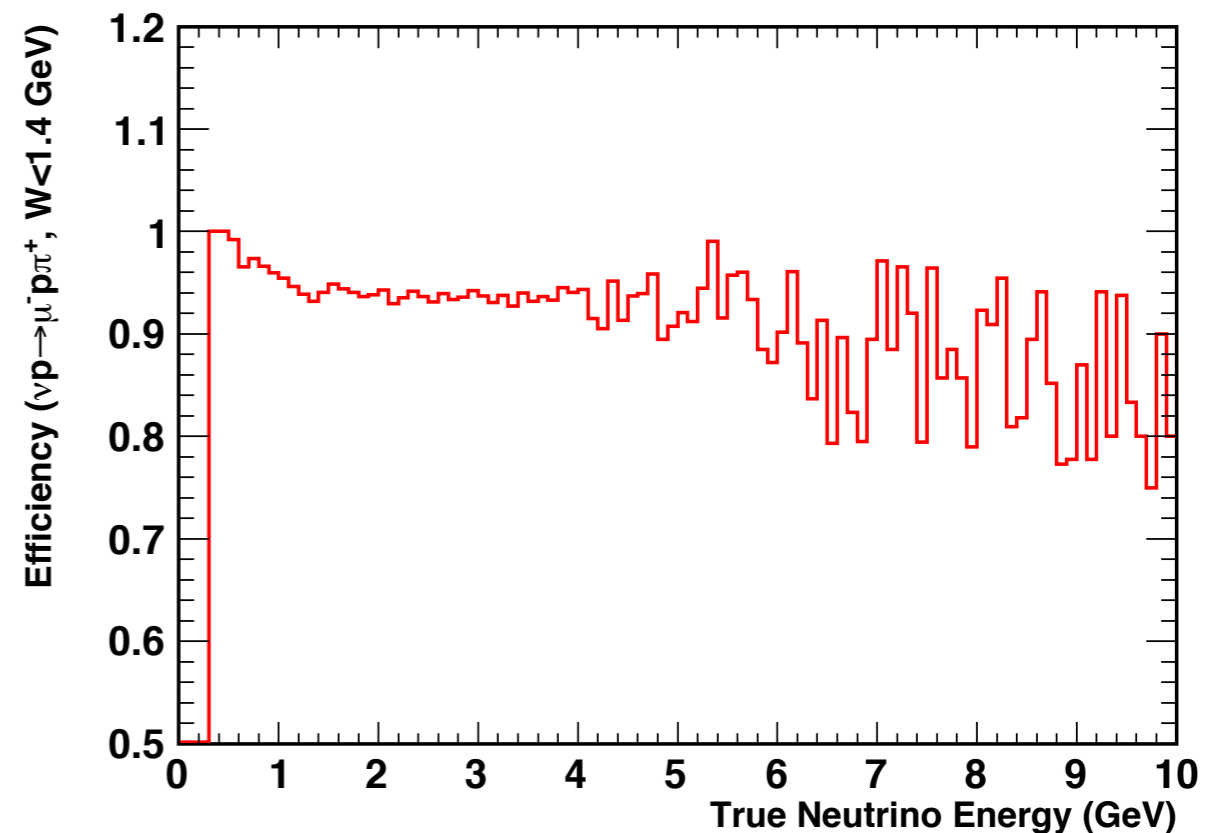


- The selection efficiency is flat for most of the energy region: the selection is independent from incoming neutrino energy.
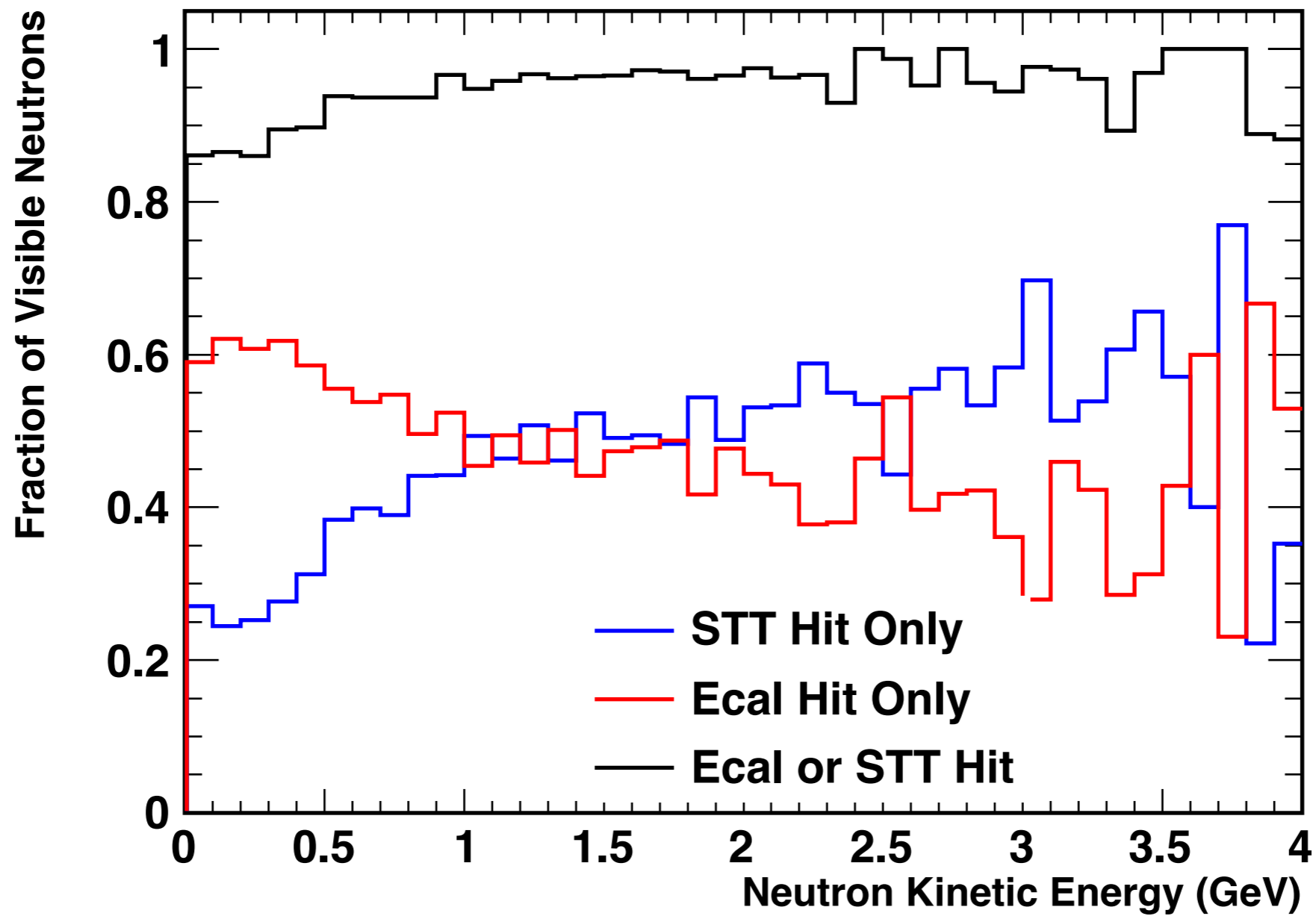
# Neutrons in STT

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- The cross-sections of $\nu$-H are better understood than heavy nucleus and <u>free from uncertainties from nuclear effects</u>.

- Two channels: $\nu p \to \mu^- p \pi^+$, $\bar{\nu}_\mu p \to \mu^+ n$
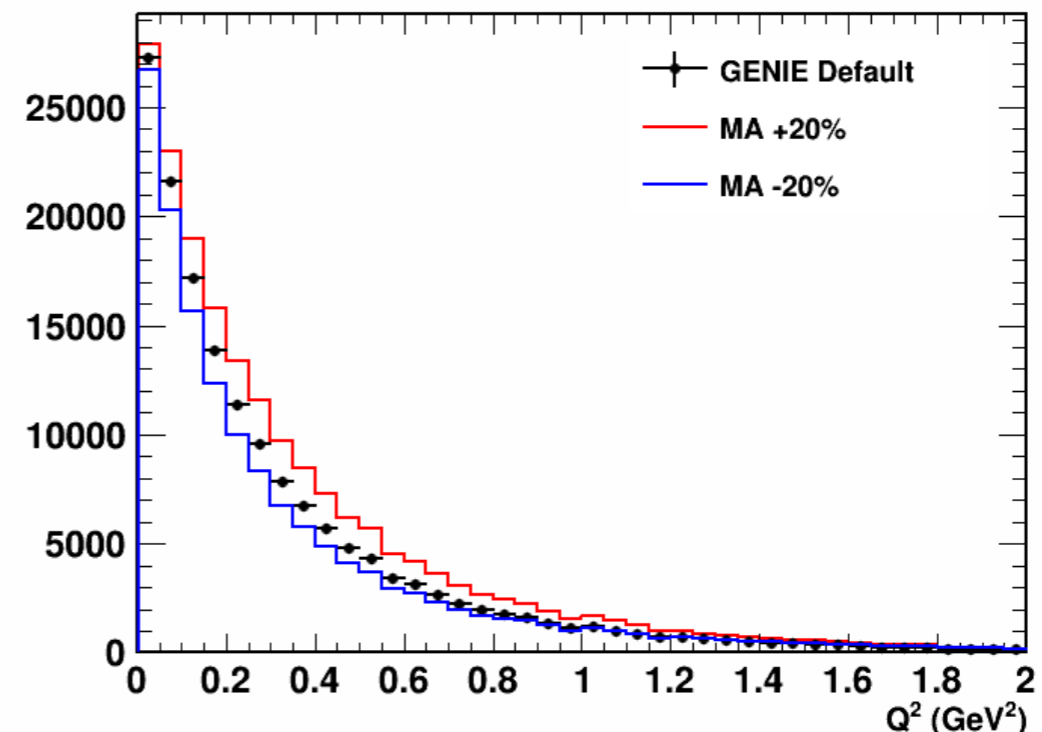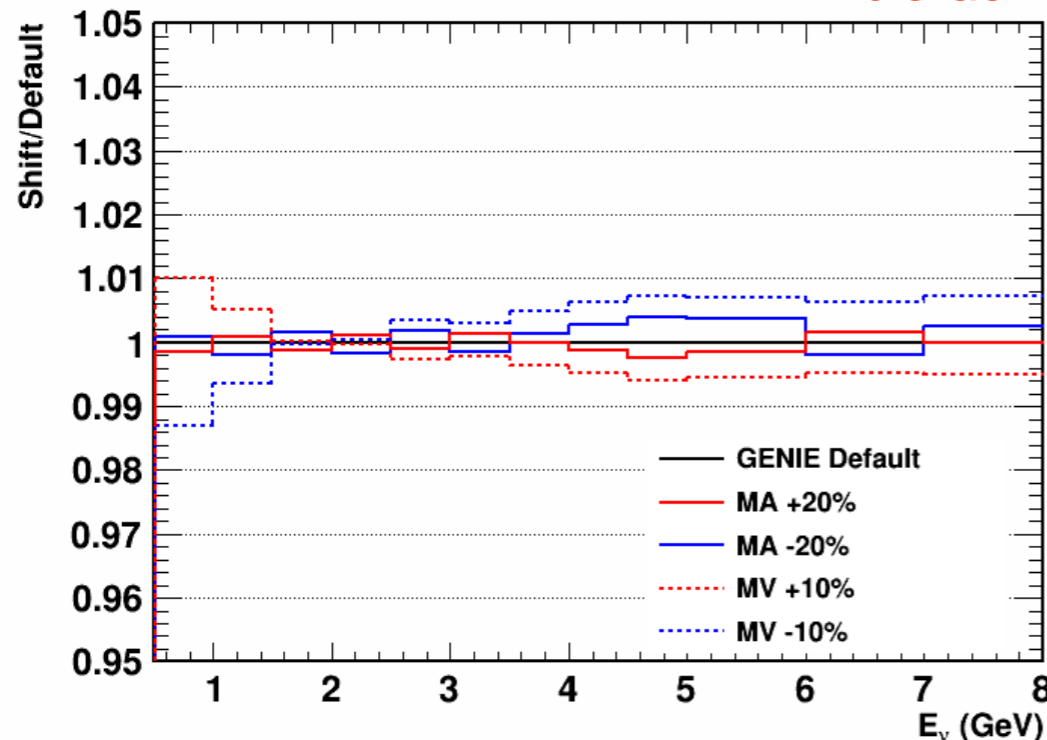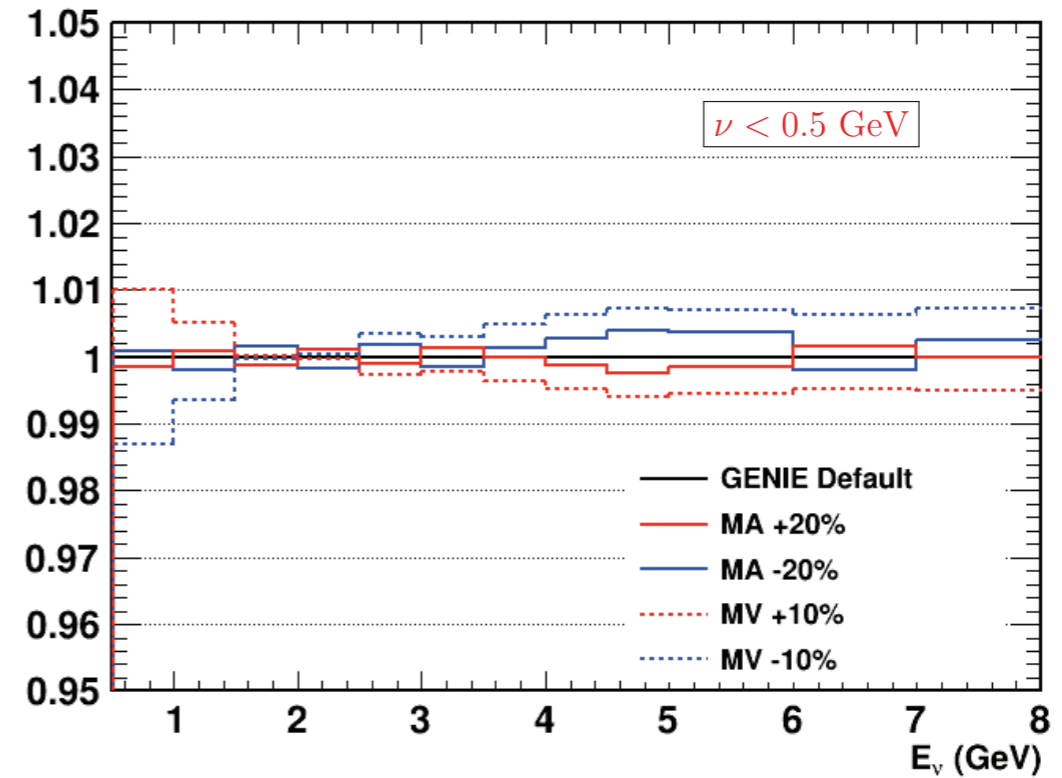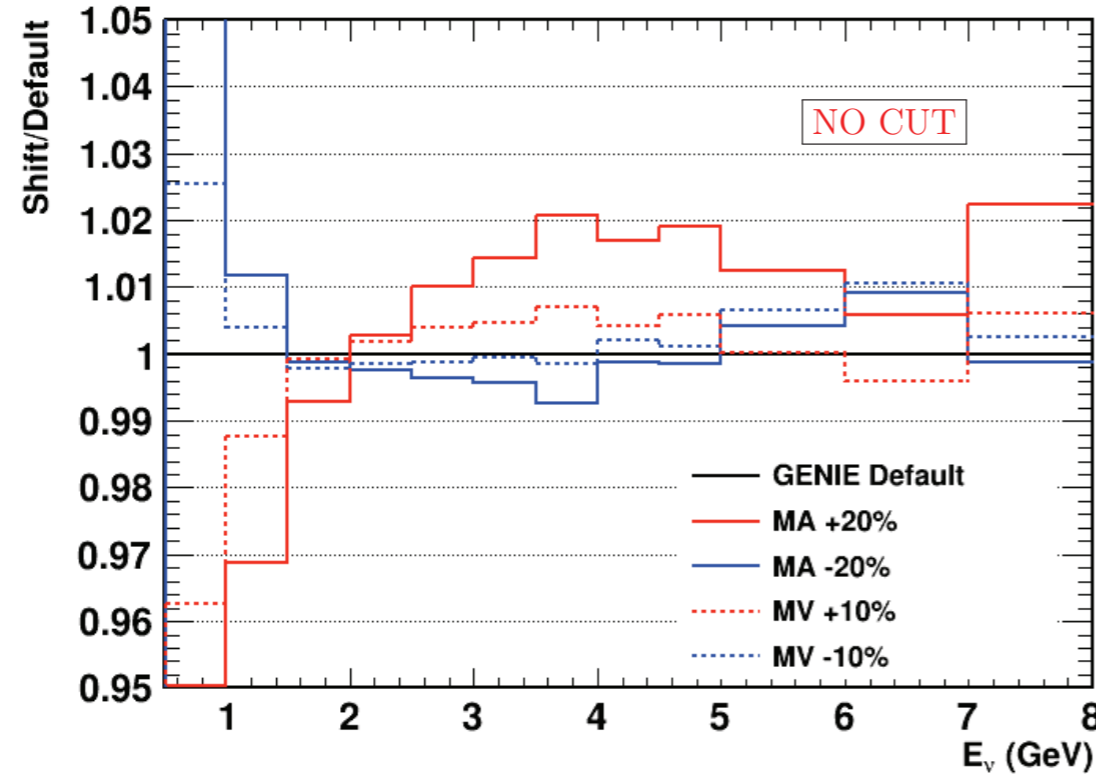
**ν<0.5 GeV**



**Uncertainties further constrained by differential measurements in inclusive sample.**
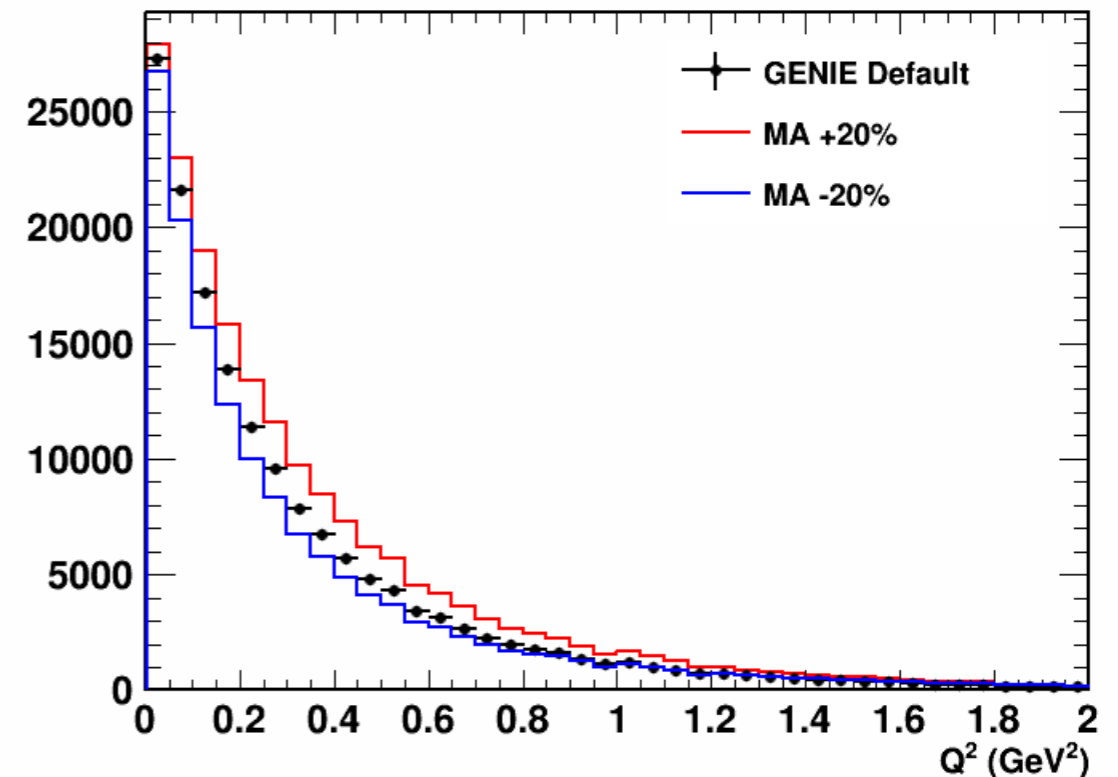
16

# Low-ν Neutrino Flux Measurement
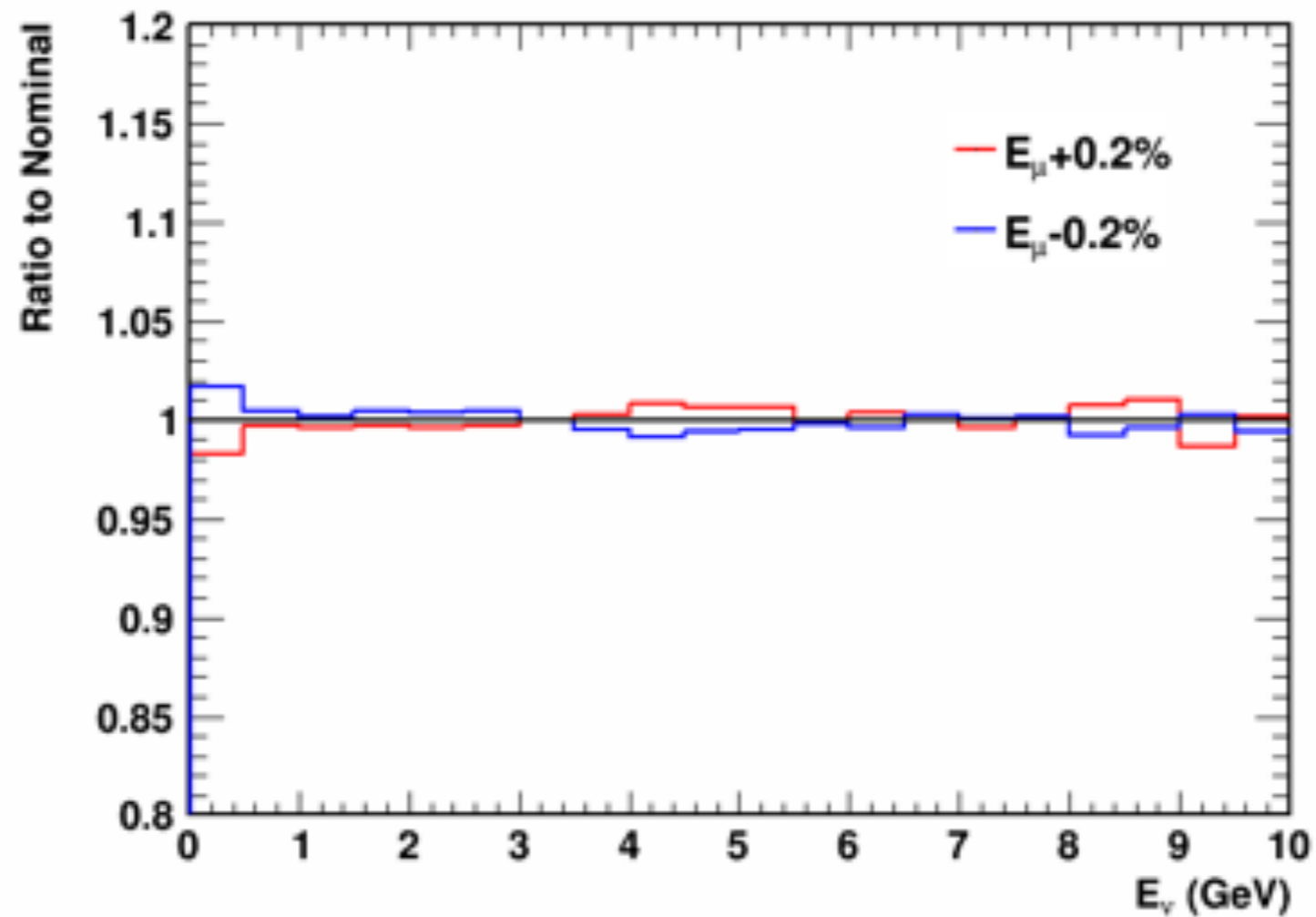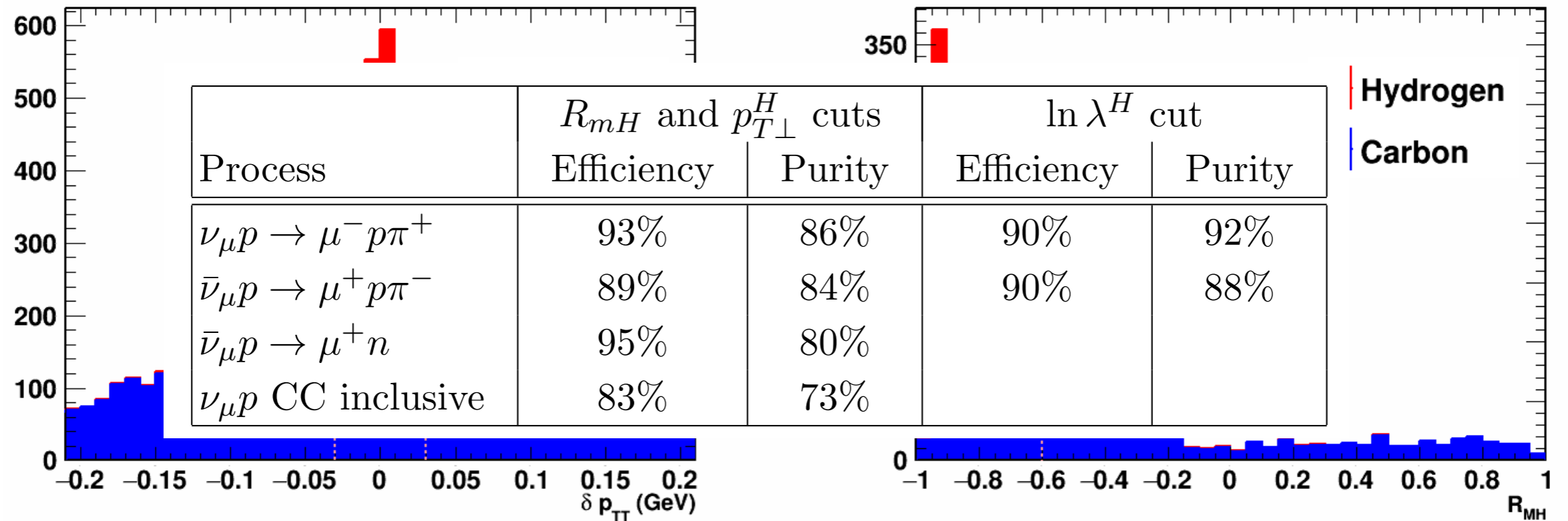


- Uncertainty from muon energy scale

# Flux Measurements (Low-ν)



- The cross-sections of ν-H are better
- Low-ν (energy transfer to hadronic s
  remaining uncertainties from hadron
- Expect 0.4M events: a precise meas

# $\nu$-H Selection



| Process | $R_{mH}$ and $p_{T\perp}^H$ cuts | | $\ln \lambda^H$ cut | |
|---|---|---|---|---|
| | Efficiency | Purity | Efficiency | Purity |
| $\nu_\mu p \to \mu^- p \pi^+$ | 93% | 86% | 90% | 92% |
| $\bar{\nu}_\mu p \to \mu^+ p \pi^-$ | 89% | 84% | 90% | 88% |
| $\bar{\nu}_\mu p \to \mu^+ n$ | 95% | 80% | | |
| $\nu_\mu p$ CC inclusive | 83% | 73% | | |

HiResM$\nu$:
Costs and Detector Design

R. Petti

*University of South Carolina*

- Similar technique is applicable to the inclusive sample sample
- Working on improving efficiency and purity.

# Flux Measurements: $\bar{\nu}_\mu$-CCQE

✦ *Measure absolute $\bar{\nu}$ fluxes from QE on Hydrogen $\bar{\nu}p \to \mu^+ n$:*

$$\frac{d\sigma}{dQ^2}\Big|_{Q^2=0} = \frac{G_F^2 \cos^2\theta_c}{2\pi}\left[F_1^2(0) + G_A^2(0)\right]$$

*where terms in $(m_l/M)^2$ are neglected.*

- *Cross-section independent of neutrino energy for $\sqrt{2E_\nu M} > m_l$;*
- *At $Q^2 = 0$ QE cross-section determined by neutron $\beta$-decay to a precision better than 1%;*

$\Longrightarrow$ *Additional theoretical $E_\nu$ uncertainties to consider?*